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THE ORIGIN OF THE PRE-CAMBRIAN BANDED IRON ORES

TAKAO SAKAMOTO

ABSTRACT. The cause of banding in the Pre-Cambrian banded iron ores is sought in a cyclical deposition of colloids due to a periodic change of reaction (pH) of lake water. The two-component poor ores, with alternating bands of ferric iron oxides and silica, are the product of an acid-neutral semi-cycle; while the three-component poor ores, with alternating bands of the above two plus a third of iron silicates (often of iron carbonates), are the product of an acid-alkaline complete cycle. The interrelation between these two types of ores seems to be one of a primary sedimentation and not of a later oxidation of the latter into the former.

Both iron oxides and silica are the products of a mature weathering. The behavior of these components in solution is supposed to have been in the same general trend as in the present soil profiles that have been generalized by the writer with his "ISOSIALS" in his recent paper (1944) on the genesis of bauxite deposits, the generalization upon chemical changes being based upon Sante Matson's experiments on the isoelectric points of soil colloids (1932).

In view of the regularity and purity of the bands as well as the vast thickness of the total iron ore beds, chemical weathering and deposition are known to have been preponderant and to have given rise to the most perfect "sedimentary differentiation" in the earth's history.

It is inferred that shallow lakes in a paralic basin and a monsoon-like climate were responsible for the unique environmental condition. That environment obtained only in the Middle Pre-Cambrian or only once in the history of the gradually cooling earth's surface, and its like has never been reproduced in any later geologic ages.

PREFACE

DURING his service, from 1924 to 1945, in the Geological Department, South Manchuria Railway Co., the writer had opportunities of visiting large and small deposits of banded iron ores in Manchuria, representing successive stages of progressive metamorphism. In 1927, he visited the Mesabi Range deposits in the Lake Superior Region, U. S., and in 1937 the Krivoy Rog deposits in the Ukraine, U.S.S.R.

In 1939, the Geological Department, with the writer as the Chief, found a magnetic anomaly of over 6,000γ in a wide area

in the plain adjacent to the An-shan deposit, which was then prospected with deep borings over a period of years. The writer again visited the deposit and found three-component ores at P'ai-chia-pu-tzu in which the original sedimentary structure was unusually well preserved.

Mr. G. Asano was then engaged in the studies on the banded iron ores and had published detailed studies in a series of papers, especially on lithologic characters of the ores. He pointed out that different deposits in Manchuria showed successive stages of progressive metamorphism, leading to the formation of eulysite.

The writer found that, if the Lake Superior and the Krivoy Rog be added to the top of the list, the series would become complete, because the bulk of the primary ore beds in these deposits consists in little-metamorphosed jaspilites.

The writer has made studies upon the mechanism of sedimentation and upon the progressive metamorphism. He has written a large paper upon the significance of the banded iron ores from the point of view of Pre-Cambrian historical geology. The present paper is a part of the larger paper, relating to the genesis of the banded iron ores.

The General Properties of the Banded Iron Ores

STRATIGRAPHY

The iron formations are found in the Pre-Cambrian rocks upon each continent, but not in all the Pre-Cambrian terranes. Their thickness is usually 100-200 m., the maximum being 450 m. in the Lake Superior region. In the latter region, they are found at three horizons in the Keewatin and the Huronian Systems. Although their age is considered to be Archean in Fennoscandia and India and in the Keewatin in North America, they are usually found among intermediate members between the most highly and the least metamorphosed rocks of the Pre-Cambrian: *e.g.*, in the Wu-t'ai (Liao-ho) System in Manchuria and North China, Saksagan System in Ukraine, Jatulian and Kalevian in Fennoscandia, and Huronian in North America.

There are iron ore beds in formations of later ages, *e.g.*, Wabana, Clinton and Oriskany in North America, Minette in Europe, Oolitic in England, etc. But these are of entirely different type, lacking in siliceous bands, and are much thinner

when compared with those of the Pre-Cambrian. The banded iron ores are characteristic of the Pre-Cambrian, and in no later geologic ages were similar iron ore beds formed.

Where the iron deposits have been highly metamorphosed, their stratigraphic position can be determined only with great difficulty, but where the stratigraphic position is clear they are found, all over the world, in Proterozoic rocks. Moreover, it is striking that, within the Proterozoic cycles of quartzite, slate and calcareous formations, they are always associated with the clay-slate.

THE ORES, THEIR BANDED STRUCTURE AND THE GRAIN SIZE OF COMPONENT MINERALS

The banded iron ores in Manchuria and other regions can be classified as follows:

TABLE 1

The Classification of the Banded Iron Ores

Banded iron ores	Poor ores	Hematite-magnetite-quartz schist	Class 1
		Hematite-magnetite-quartz schist or magnetite-quartz schist with siderite, chlorite, gruenerite, cummingtonite, hornblende, pyroxene, garnet or olivine	Class 2
	Rich ores	Sedimentary — Hematite-magnetite-quartz schist	Class 3
		Hydrothermal — Magnetite or martite rock with chlorite and dolomite	Class 4
		Weathering — Limonite, hematite and martite	Class 5

The bulk of the banded iron ores in Manchuria consist of the hematite-magnetite-quartz schist (Class 1) or the poor ores with alternating bands of iron oxide and silica which correspond to jaspilites of Lake Superior and Krivoy Rog, only recrystallized and with coarser grain. The rest of them consist of finer-banded poor ores with alternating bands of three components, *i.e.*, iron oxide, silica and iron silicates (often iron carbonates). This second group occurs in An-shan in thick beds in locally restricted areas, *e.g.*, in Yuen-chien-shan and Ta-ku-shan areas. Those poor ores which contain amphiboles, pyroxenes or olivines represent successively higher-metamorphosed members of the group (Class 2), becoming similar with a eulysite in Sweden at their extremity. They occur

at Miao-erh-kou, Wai-tou-shan and to the south of Fu-shun, being accompanied either by mica schists or by migmatite gneisses. In the northern part of Krivoy Rog and in Vermilion Range to the east of Mesabi, are also found poor ores of this type.

The rich ores (Class 3) are found in local areas in Krivoy

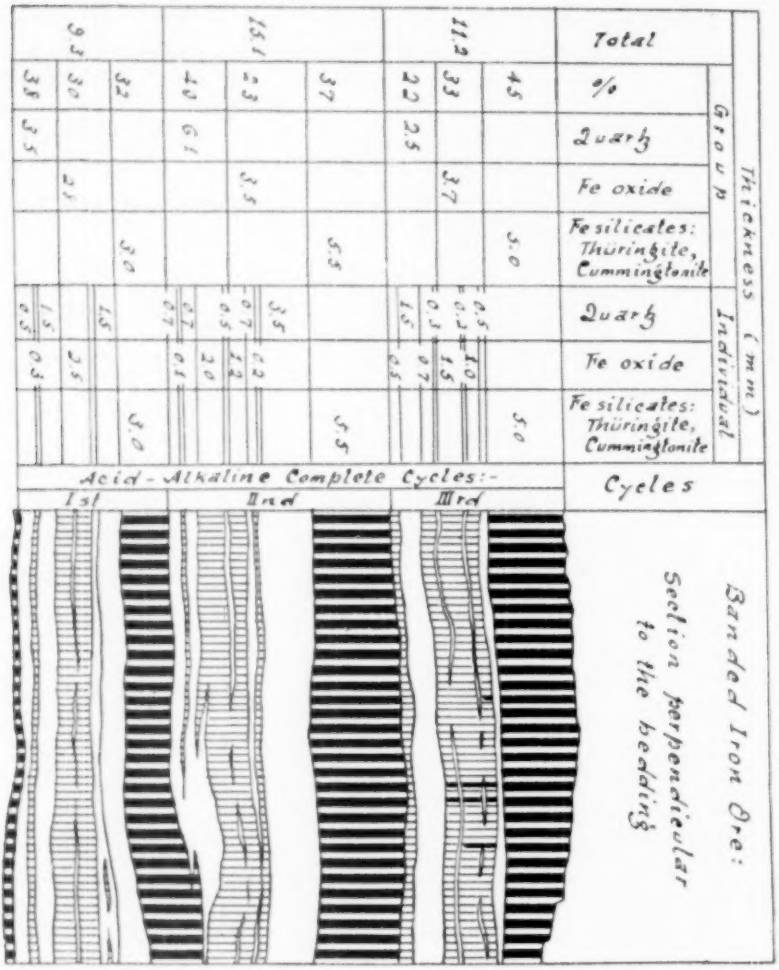

Figure 1. Cyclic banding in the banded iron ore from P'ai-chia-pu-tzu, An-shan.

Rog and An-shan, but their mode of formation has not yet been determined. The big deposit in Brazil is thought to be of this class. The ores of Class 4 are found in Krivoy Rog and in Miao-erh-kou. The ores of Class 5 form vast deposits in Central India, Lake Superior and Krivoy Rog regions. From an economic standpoint the value of the banded iron ores throughout the world rests on the rich ores of Class 5.

TABLE 2

The Width of Bands and the Grain Size of Component Minerals

Ores	Width of bands (mm.)		Diameter of mineral grains (mm.)	
Two-component poor ores	Finely banded	0.5- 2	Iron-minerals	0.005-0.3
	Coarsely banded	2 -10		
Three-component poor ores	Silica bands	0.2-3		
	Fe oxide bands	0.2-2	Quartz	0.05 -0.5
	Chlorite bands	3 -5.5		

The above diameters of mineral grains are those of ordinary

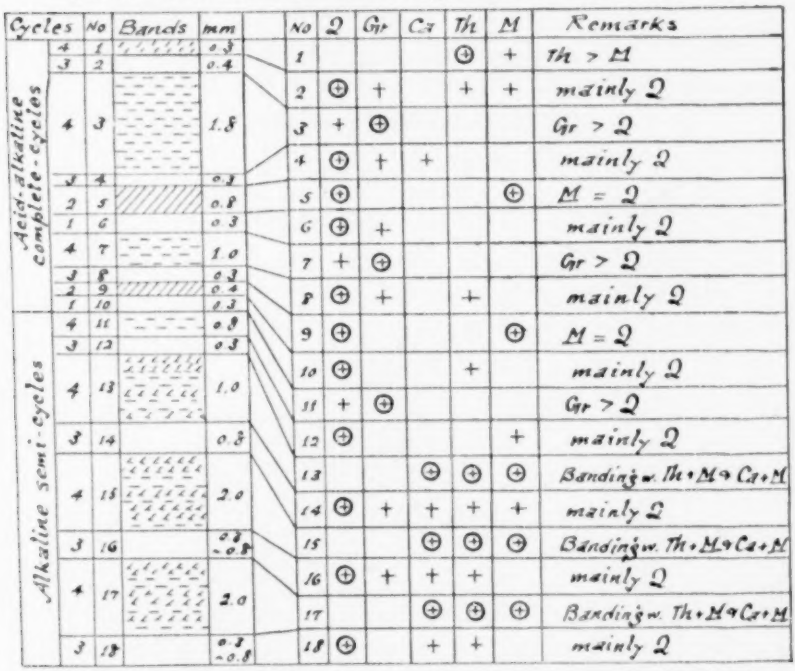

Figure 2. Banding and mineral components of gruenerite-thueringite-magnetite schist at Yuen-chien-shan. *Q*, quartz; *Gr*, grünerite; *Ca*, siderite; *Th*, thüringite; *M*, magnetite; ⊕, main component, (Materials after G. Asano).

hematite-magnetite-quartz schist or cummingtonite-magnetite schist in An-shan district. Those in jaspilites in foreign deposits are much smaller, while those in metamorphosed ores are a little larger.

It is remarkable that such fine bands should be piled up in beds, showing regular cycles, and should attain thickness of tens or even hundreds of meters without any interrupting beds of other sediments.

Examples of bands and regular cycles of three-component poor ores, which are exceptionally well preserved in some ores in the An-shan deposit, are graphed in figures 1 and 2.

G. Asano recently published very detailed studies upon the An-shan deposit and stated his views on the banded structure as follows:

"At the time of deposition, they were deposited as thin bands

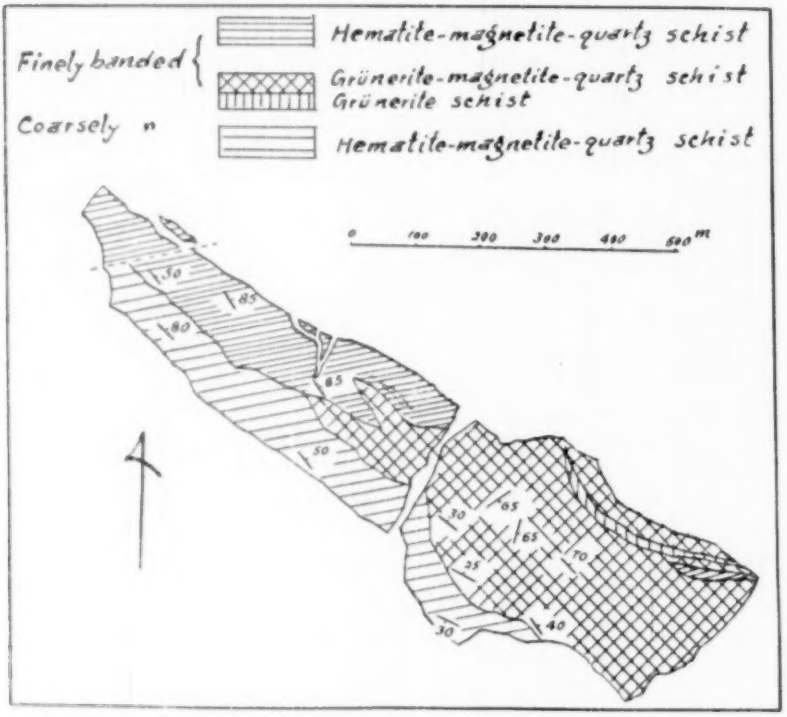

Figure 3. Ta-ku-shan ore body showing the distribution of different types of the banded iron ores (after G. Asano).

with different components and later partially oxidized and then subjected to regional or thermal metamorphism. According to their original constituents, they are either simply recrystallized or changed into certain suite of new minerals that are in equilibrium under new conditions. Since such suite become different from each other as the original constituents are different, they again result in different component minerals in each of the thin bands (Asano, 1941, p. 37)."

Asano further gives the following description regarding the mode of occurrence of three component ores with gruenerite, cummingtonite, thueringite and siderite:

"Both at Yuen-chien-shan and Ta-ku-shan, ores with amphiboles occupy the whole thickness, from top to bottom, of the iron formation, but only in certain locally restricted areas among two component poor ores. When traced laterally in their prolongation, they entirely disappear from every horizon of the iron formation."

That is, the whole of a given iron ore bed may change from two-component into three-component ores according to locality and not to stratigraphic horizons (see fig. 3).

EARLIER VIEWS REGARDING GENESIS

Earlier views regarding genesis are summarized in the following table:

There seems to be a consensus of opinions as to the sedimentary origin of the poor ores. That they are formed by silicification of tuffs, as recently postulated by Dunn, is a unique view.

The Process of Sedimentation and the Formation of the Banded Structure

POSITION OF THE IRON FORMATION IN THE PRE-CAMBRIAN CYCLE OF SEDIMENTATION

Deformation and progressive metamorphism of the Pre-Cambrian rocks containing the banded iron ores has in many places produced badly folded and contorted crystalline schists and gneisses, rendering determination of thickness as well as of the nature of the original sediments very difficult. However, in less metamorphosed areas, the iron formations are clearly interbedded with quartzite, clay-slate, limestone, etc., and not

TABLE 3

Earlier Views Regarding the Genesis of Pre-Cambrian Banded Iron Ores

Genesis of poor ores

		Raw materials	Transportation and deposition	Environment of deposition	Authority
Aqueous sedimentation	Lake Superior	Weathering products of volcanic rocks Magmatic solution	Chemical deposition	Sea bottom	Van Hise & Leith, 1911
		Weathering products of volcanic rocks	Transported as colloids protected by organic matter, deposited by bacteria	Lake bottom	Gruner, 1937
		Weathering products of Pre-Cambrian rocks	Transported as colloids protected by organic matter, deposited by electrolytes	Lake bottom	Moore & Maynard, 1929
	An-shan	Weathering products of basal metamorphics	Deposited by bacteria	Marsh	Murakami, 1922
	Krivoy Rog	Lateritic weathering products of Archaean gneiss	Transported as colloids protected by organic matter, deposited by electrolytes	Lake bottom	Svitalsky, 1937
	Middle Sweden	"Volcanic solution"	Chemical precipitates	—	Magnusson, 1936
	Western Australia	Weathering products on peneplain	Chemical precipitates	Peneplain	Woolnough, 1941
Replacement	Lake Superior	Volcanics	Ascending hot solution	—	Collins, Quirke & Thomson, 1926
	India	Banded tuffs	Hot spring	—	Dunn, 1941

Genesis of rich ores

Genesis	Ore deposits	Ores	Authority
Weathering:—dissolution of SiO_2 by descending meteoric water	Lake Superior	Red hematite, limonite	Van Hise & Leith, 1941
	Singhbhum, India (float ore, blue dust)	Black hematite	Dunn, 1941
	Part of Krivoy Rog	Limonite	Svitalsky, 1937
Hydrothermal:—replacement by ascending hot solution	Lake Superior	Red hematite, limonite	Gruner, 1937
	Part of Krivoy Rog	Martite, magnetite	Svitalsky, 1937
	Miao-erh-kou	Magnetite	Tsuru, 1931
Sedimentation	Part of Krivoy Rog	Magnetite, hematite	Svitalsky, 1937
	Brazil	Magnetite, hematite	Leith & Harder, 1911

only accurate measurement of their thickness but also close observations upon their environments of deposition are possible.

In the Lake Superior area, the main iron formations (Biwabik and Ironwood) belong to the Middle Huronian, while there are other iron formations in the Upper and Lower Huronian. The Upper, Middle and Lower Huronian Systems each reaches nearly 1,000 m. in thickness. Each begins with a quartzite at its base, comprises thick clay-slate and marl or limestone in an ascending order; each shows a normal cycle of sedimentation. That is, normal cycles were repeated three times, each attaining a remarkable thickness. Besides, what is worth attention is that the iron formation in each case is associated with the clay-slate. The iron formations themselves reach thicknesses ranging from several meters to 450 m.

At Krivoy Rog, there is a quartzite at the base, next a thick phyllite, and above an alternation of phyllites, carbonaceous slates and limestones. The iron formation is associated with the phyllites. It occurs in a complicated synclinorium, so that the measurement of thickness is difficult. According to Svitalsky (1937), however, the thickness is around 50 m. on an average, but near Ingulets Mine it reaches the tremendous figure of 1,500 m.

At Singhbhum in India, also, the newer Dharwar series, which contains the iron ore series, consists of sandstones and occasional conglomerate below and of shales above, the iron ore series being situated between the "Lower shales" and the "Upper shales" (Jones, 1934).

At An-shan, later granitic intrusions and overthrusts render the measurement of thickness difficult. Both hanging wall and footwall of the iron formation consist of intensely folded, gray, graphitic slate and phyllite. Those in the hanging wall are intercalated with beds of a black limestone. In those parts close to the contact with the iron ore beds, the cleavage of the slate and phyllite is usually parallel with the plane of contact with the ore, and consequently is apt to be mistaken for the bedding of the slate and phyllite. Therefore, the thickness of the latter is difficult to determine accurately but a reasonable assumption is over 900 m.

As stated above, the Pre-Cambrian systems show normal cycles of sedimentation and attain a remarkable thickness. Such large cycles as these are not always found in later geologic systems. This testifies that the Pre-Cambrian environments of sedimentation were unique.

THE MATURE WEATHERING

The fact that the iron formations in these cycles are always associated with clay-slates or phyllites, shows that the source of the materials of the ore beds may be found in the weathering and sedimentation in the particular environment under which the clay-slates or phyllites were produced, and that the views, long entertained in some quarters, that the iron was derived from submarine volcanoes or special volcanic rocks, are quite untenable. The ferruginous material should be reckoned as the product of mature weathering on a land surface. Indeed, iron oxide, free silica and aluminum hydroxide are three main products of mature weathering. Iron oxide and silica are constituents of all the banded iron ores, while the presence of aluminum hydroxide is not prevalent. According to Dunn (1941), however, frequent occurrence of kyanite and sillimanite deposits in the "Gondite series" of the Pre-Cambrian in India are derived from aluminous sediments, which in turn might have originated from ancient bauxites. According to

this view, the Pre-Cambrian of India contains all three main products of mature weathering.

According to recent observations by Woolnough in western Australia, there is widespread formation upon the surface of peneplaned regions of colloidal deposits, called by him "duricrusts," which have different chemical compositions according to the nature of the country rocks. Woolnough believes that the Pre-Cambrian banded iron ores were formed in the same way as these "duricrusts" upon a peneplain (1941).

Disregarding the presence or absence of all of the above three constituents at the same time, at least the development of such a large cycle and its regular repetition clearly point to constant physiographic and meteorologic conditions over a long period of time. Accordingly, after a period of deposition of a quartzite and like coarser materials, in the stage of deposition of finely divided suspensoid or colloid like clay-slates, the land became low and flat, and chemical weathering became predominant over a long period of time. Under such an environment of weathering, silica in colloid form and partly in true solution, is removed from the weathering crust and accumulates in basins. The physiographic condition of the sedimentation of the Huronian System is believed to have been shallow seas or inland lakes and not open seas (Leith, 1934, pp. 157-158).

That the land surface was generally flat and lacking in steep topography is inferred from the long history of extensive weathering (being continued from the active primordial weathering in the Archean), and from the lack of coarser conglomeratic sediments comparable with those of the neo-Proterozoic and later systems. The movement of the earth's crust was perhaps epeirogenic rather than orogenic. T. Kobayashi, in his discussion on the sedimentational facies of the Sinian System in Manchuria and Korea believes that the tract as a whole had the nature of a kratogen (Kobayashi and Nakano, 1942).

Iron migrates in acid environments and is precipitated in neutral and alkaline environments. Silica, on the contrary, migrates in alkaline and is precipitated in acid environments. That this holds in the zone of weathering has been quantitatively established by experiments on "isoelectric points" by Mattson (1932). The writer, in his former study

on the weathering and sedimentation of bauxites and bando-ketsugan (aluminous shale), found that the distribution of soil colloids is in close connection with the acidity of the environment and that the results of Mattson's experiments are in good harmony with the distribution of soil colloids in the natural soil profile. The writer then found that the systematic distribution of soil colloids in a generalized soil profile of humid soils throughout the cold, temperate and tropical zones, could be shown graphically (fig. 4) by means of "equal silica-alumina molecular ratio lines, deeper in the soil profile toward the south, for which the writer proposed a new term "ISOSIALS" (Sakamoto, 1944).

What can be deduced with certainty from the generalized soil profile is that the soil solution above the water table, except in arid regions or seasons, is acidic, the acidity being highest in the cold zone in higher latitudes; whereas the solution below the water table, disregarding the climatic zones and seasons, is always alkaline (pH 8±). Iron is dissolved by acid soil solution above the water table, resulting in a bleached soil, called a podsol, in regions of higher latitudes. Iron thus dissolved, upon reaching the water table below where the soil solution becomes neutralized, is precipitated as iron hydroxide, sulphide or phosphate and cements together fine particles of clay suspensoid, giving rise to the so-called "ortstein," or a compact and impervious hardpan. In humid seasons when soil solutions freely circulate and show a high acidity, part of the iron in true solution in the form of bicarbonate, etc., migrates to depressions and rivers and finally is precipitated in basins or on sea bottoms.

Silica is dissolved by alkaline water below the water table, the reaction being most manifest in the case of a laterite profile in the tropics. Rocks are deeply weathered, large quantities of alkalies are set free, mainly in the form of alkali carbonates, and the soil solutions become alkaline with pH around 8.

In this alkaline environment, replete with cations, clay colloids with the SiO_2:Al_2O_3 molecular ratio around 4 adsorb alkali and alkaline earth ions and form thick zones of bentonite. In upper horizons closer to the phreatic zone where soil solutions, more dilute with ions, migrate freely, those adsorbed cations are dissolved. Bentonites, becoming unstable, are easily desilicated and become clay colloids with a SiO_2:Al_2O_3 molecu-

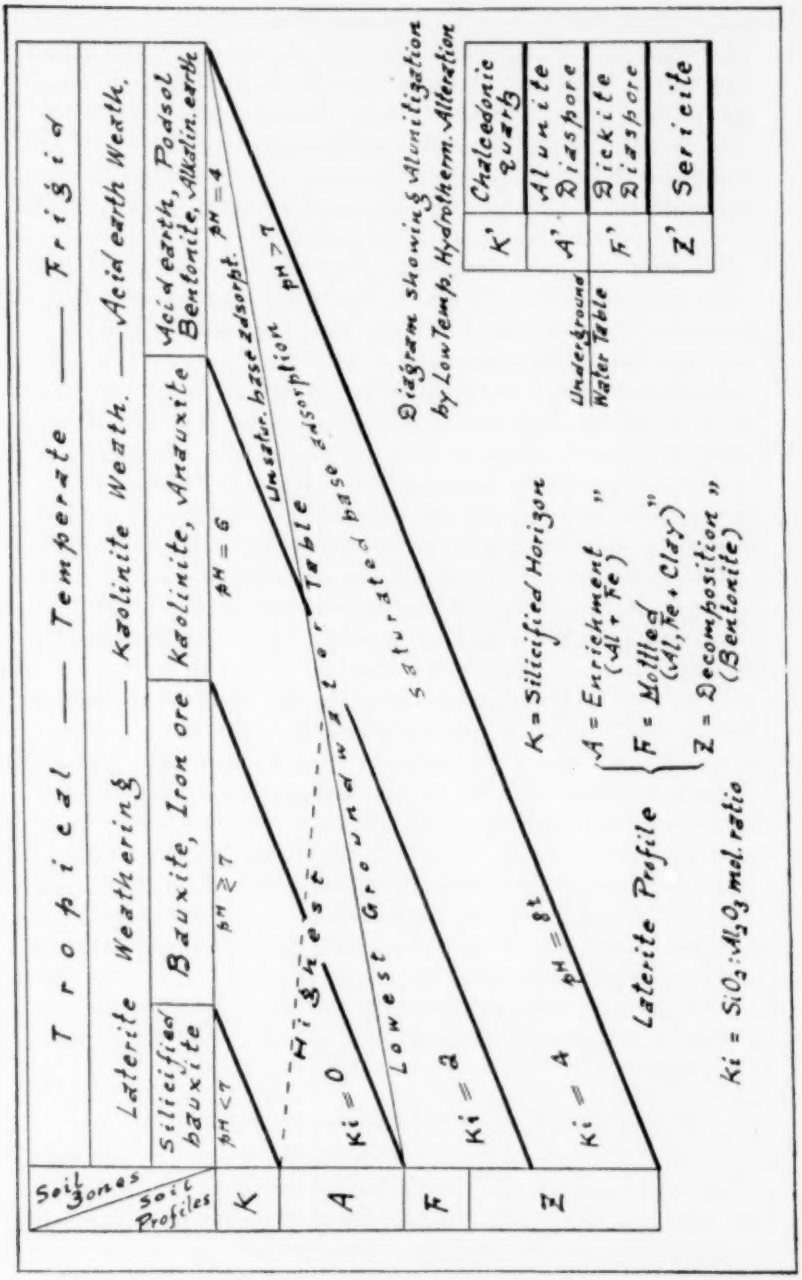

Figure 4. Diagram showing "ISOSIALS" or equal SiO_2:Al_2O_3 molecular ratio lines in natural soil zones and profiles.

lar ratio around 2, or a clay corresponding to a kaolinite. Still higher at the base of the phreatic zone, where horizontal flow of the underground water reaches its maximum, desilication is accelerated, finally setting iron and alumina free to form laterite. Where the underground water table fluctuates up and down in wet and dry seasons, as upon the surface of flat plateaus or low hillocks under a monsoon climate, lateritic iron ores and bauxite deposits are formed.

The process of laterization is thus desilication by alkaline underground water produced by the deep weathering characteristic of the tropical zone, with the formation of iron ores and bauxites as its end-product.

The iron ores and bauxites thus formed lose their iron when the environment becomes acidic, owing either to the coming back of a forest or to covering by peats. The bleached portion assumes a mesh appearance in plan and "schecken" or bands in vertical section. Also, in bauxite deposits, either the superficial portion, several decimeters thick, becomes bleached and silicified or the whole deposit becomes penetrated with light-colored kaolinite pipes with a funnel shape. This phenomenon may be taken as a retrogression of the iron and bauxite deposits.

In short, among the soil colloids, the most stable components remain and unstable components are dissolved out according to the acidity of the environment. Taking into account the above-stated facts, it is known that the iron in the acid environment above the water table and silica in the alkaline environment below the water table are both unstable and migrate until they reach an opposite environment where they are redeposited. Especially, in the profile above the water table in regions of higher latitudes, the environment is highly acidic, and iron (plus part of the alumina) is dissolved, whereas in the profile below the water table in the tropics the environment is highly alkaline, and silica is extensively dissolved and removed.

TRANSPORTATION AND DEPOSITION OF THE PRODUCTS OF WEATHERING

Taking these facts into consideration along with the inference above concerning Pre-Cambrian environmental conditions of weathering, a gleam of light seems to be thrown upon the

question of the accumulation of the unusually large quantities of iron and silica. The lack of coarse debris and the thick and normal cycles as in the Lake Superior area point to mature weathering as has already been pointed out by Prof. Leith (1934). Also, it is generally accepted that the Pre-Cambrian atmosphere was very rich in CO_2 gas. Under such physiographic conditions chemical weathering predominates, and, especially when the atmosphere contains much CO_2, the surface water in contact with it can retain much bicarbonate in solution whose vapor pressure is in equilibrium with the large pressure of CO_2 in the atmosphere. In other words, rocks are rapidly decomposed, giving rise to deep weathering.

Supposing that the annual rainfall was great and divided into periodically wet and dry seasons, shallow grounds above the water table became neutral or even alkaline in a dry season and the phreatic zone near the water table became neutral or temporarily even acidic in a wet season. (This is the condition which obtains under the present tropical monsoon.) In wet seasons, iron migrated in the acidic surface water, while in dry seasons, silica migrated in the alkaline ground water. The iron and silica, though partly consumed in the formation of ferruginous "ortstein" or local silicification of country rocks, mostly went into solution and were transported into basins and depressions to be precipitated there as the sediments of "fernfaellung."

Suppose further that these basins and depressions were wide but shallow, and were separated from the open sea with only low barriers. When there was much influx of surface water in wet seasons, the lake water easily overflowed into the sea; when the influx was stopped in dry seasons, the lake became an inland lake in an arid region. When the lake water became acidic in wet seasons, and cool water with free oxygen circulated down to the bottom by convection, then the whole lake water became acidic and oxidizing. In dry seasons, on the contrary, the influx of fresh oxygen-bearing and oxidizing water was stopped, and the lake water became neutralized owing to seepage of alkaline underground water. Owing to evaporation, the lake at last became an inland lake in an arid region in which the water stayed stagnant, oxygen was lost and, as the level of the lake water went down, its reaction became alkaline. In the next wet cycle, a fresh influx began and as

the level of the lake water arose, the reaction became neutral and finally, when it began to overflow, acid again.

Similar phenomena can be observed at present in rivers and lakes in the semi-arid region in north Manchuria. In the River Sungari, pH falls in flood seasons in summer, and rises in low water in winter. The water in many shallow lakes in the semi-arid steppe around Hailar, north Manchuria, is all weakly to strongly alkaline and none is acid.

In a lake where the reaction of water repeats regular cycles of acid-neutral-alkaline-neutral-acid, the conditions under which silica and iron are precipitated are inferred as follows:

The iron in the form either of colloids or of true solution is supplied to the lake in wet seasons. Ferrous iron is oxidized into ferric iron due to aeration. Then, in arid seasons, when the influx of surface water is stopped and the pH of the lake water gradually rises to neutral, ferric hydroxide is precipitated very rapidly, because its isoelectric point is pH 7. A little iron still remains in the solution. Due to the seepage of underground water and evaporation, the reaction becomes alkaline. Then silica is supplied to the basin in colloidal solution, gradually increasing its concentration as the evaporation goes on. Under an increased alkaline condition, colloidal silica and iron hydroxides combine with each other to form iron silicates (greenalite, chamosite, etc.), and the rise of temperature accelerates the precipitation of carbonates of iron and other compounds. Again, upon the return of a wet season and influx of fresh surface water, the reaction returns through neutral back to acid again. In this stage, silica is totally precipitated, and the lake water is acidic, contains free oxygen and receives a new supply of iron in solution. Thus the second cycle is started and repeated.

FORMATION OF THE BANDED STRUCTURE

The relation between the periodic change of the reaction of the lake water and the supply and deposition of elements is shown schematically in figure 5.

The reaction of the water, beginning with acid (say pH 5±) at A, passes neutral (pH 7) at N and reaches alkaline (say pH 9±) at B; then returns through neutral at N′ back to acid at A′, completing the cycle. The supply and deposition

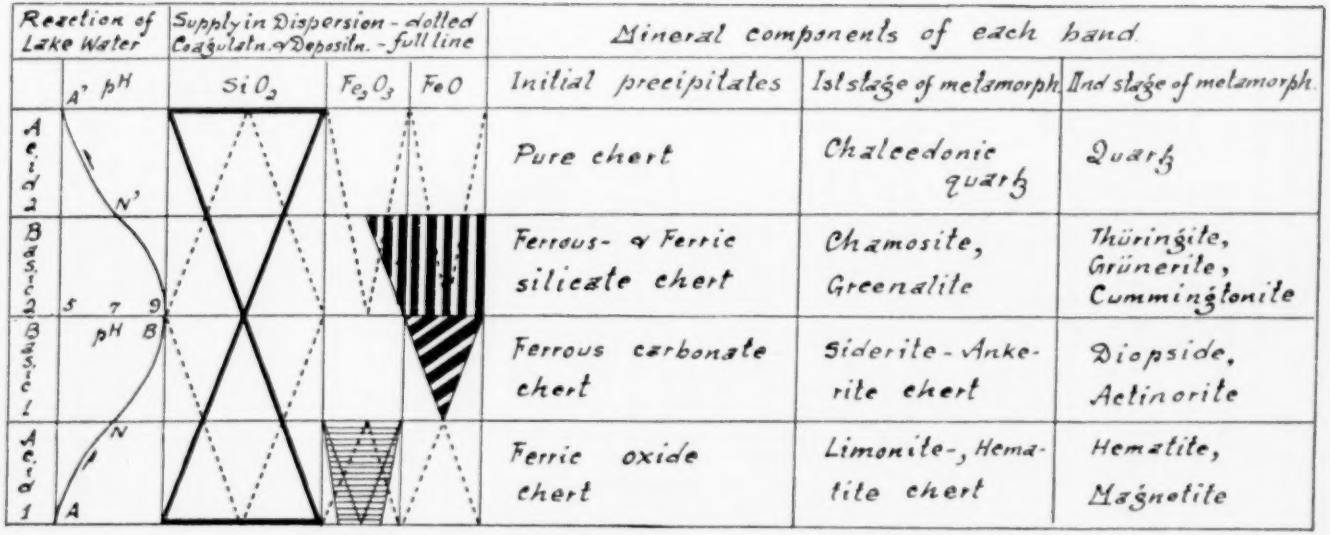

Figure 5. Supply and deposition of SiO_2, Fe_2O_3 and FeO in relation to reaction of lake water, resulting in regular banding with corresponding mineral components.

of each constituent are indicated by the areas cut, respectively, by the dotted and the full lines in the column of each constituent. The process in each of the four stages of one cycle is shown in the following table:

TABLE 4

The Sequence of Sedimentation Resulting in the Formation of Banding

Reaction & Stage		Supply & deposition	Products (Bands)
Acid 1 A — N	SiO_2	Sup—gradually increases from minimum Dep—as chert, gradually decreases	
	Fe_2O_3	Sup—decreases from maximum to minimum Dep—as limonite, concentrates in this stage, reaching maximum at N	Ferric oxide chert
	FeO	Sup—decreases from maximum to minimum Dep—none	
Basic 1 N — B	SiO_2	Sup—increases to maximum Dep—as chert, decreases to minimum	
	Fe_2O_3	Sup—none Dep—none	Siderite chert
	FeO	Sup—none Dep—as siderite & greenalite begins and increases	
Basic 2 B — N'	SiO_2	Sup—decreases from maximum Dep—as iron silicates, gradually increases from minimum	Chamosite greenalite
	FeO & Fe_2O_3	Sup—begins Dep—as iron silicates, completed	
Acid 2 N' — A'	SiO_2	Sup—decreases Dep—as chert, increases to maximum	Pure chert
	FeO & Fe_2O_3	Sup—increases to maximum Dep—none	

The concentration of electrolytes (dissociated ions of salts of alkalies and alkaline earths in the solution in the above cycle is at a minimum at A and a maximum at B. According to the experiments by Moore and Maynard (1929), "hydrosols of iron and silica stabilized by organic matter are preferentially precipitated by electrolytes with the same composition and concentration as in natural sea water. Iron is instantly pre-

cipitated while silica is precipitated much more slowly and incompletely."

As the concentration of electrolytes increases at the stage A-N in fig. 5, the deposition of ferric hydrosol is doubtless intensified; that of silica is partly deferred to the next stage N-B where, being mixed with carbonates, it forms a siderite chert. The deposition of carbonate here is accelerated by the increase of temperature.

When the concentration of electrolytes reaches its maximum, ferric and ferrous iron combine not only with silica but also with Mg, Ca and Al, giving rise to new silicate minerals. Bauer in Africa has noticed that such laterite constituents as free silica and free alumina recombine to form a chlorite, resulting in a sort of silicification in alkaline inland lakes in the tropics. Moreover, such iron ore beds as the Wabana, the Minette and the Oolitic are characterized by chamosite as one of the main iron minerals. These iron ore beds were all deposited in sea water, and, hence, under a weakly alkaline condition. These facts bear witness to the formation of iron silicates of the chlorite family at the stage B-N′.

That silica is less sensitive to electrolytes than iron is also known by the experiments of Moore and Maynard. On the other hand it is very sensitive to change of acidity, as is very well known from observations of natural soil profiles.

Figure 6 shows a profile of a shallow lake upon whose bottom banded iron ores are being deposited. The supply and deposition of different constituents are schematically shown in the profile.

The level of the lake water is at its highest when the reaction is acidic (A), medium when neutral (N & N′) and lowest when alkaline (B). The reaction of lake water and corresponding sediments and their areal distribution on the lake bottom are summarized as follows:

TABLE 5

Reaction of Lake Water and Corresponding Sediments

Stage & reaction	Sediments (Bands)	Area of deposition
A — N (Acid 1)	Ferruginous chert	Entire lake bottom
N — B (Basic 1)	Siderite chert	Small area around center of lake
B — N′ (Basic 2)	Chlorite	Small area around center of lake
N′ — A′ (Acid 2)	Pure chert	Entire lake bottom

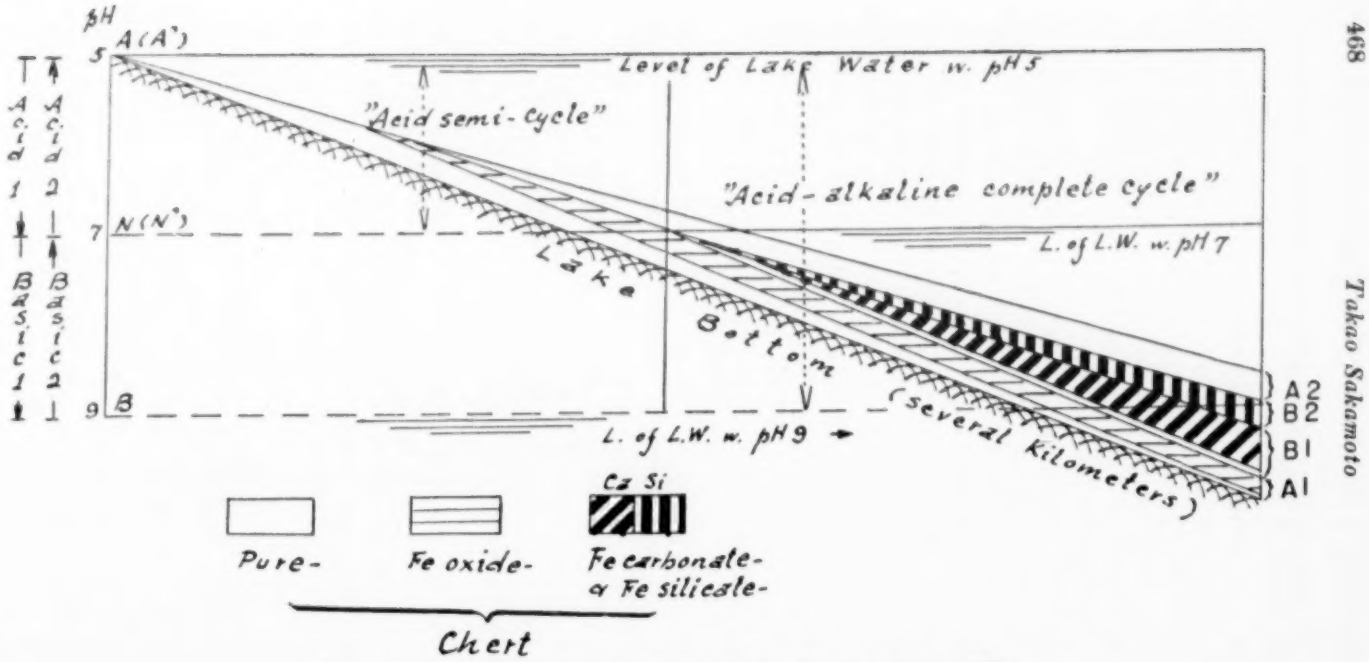

Figure 6. A diagrammatic cross section showing the deposition of SiO_2, Fe_2O_3, ferrous carbonate, ferrous and ferric silicates in relation to the reaction of (pH) and change of level of lake water. The deposit representing a cycle, A1 to A2, has total thickness of 15 mm.

In case of a complete cycle or a cycle with successive stages of acid-neutral-alkaline-neutral-acid as is seen in this figure, the sediments should be, from the bottom upward, a ferruginous chert, siderite and chlorite chert, and pure chert, thus giving rise to a distinct banding. Three-component poor ores are deposited in the deeper portion near the lake center; two-component poor ores in the shallow marginal portion.

In the case of an incomplete cycle or a cycle with successive stages only of acid-neutral-acid (a cycle which may be called an acid semi-cycle), two-component poor ores are deposited all over the lake bottom. In the case of an incomplete cycle of neutral-alkaline-neutral (a cycle which may be called an alkaline semi-cycle), three-component poor ores are deposited around the lake center.

The banded structure described in the foregoing pages, especially the one in the specimen collected by the writer at P'ai-chia-pu-tzu, An-shan (fig. 1), shows a remarkable coincidence with the banding in the acid-alkaline complete cycle in figure 6. Alkaline semi-cycles beside acid-alkaline complete cycles are shown in the banding of the ore from Yuen-chien-shan taken by Asano (fig. 2).

It has been stated above (and see fig. 3) that each of the two-and three-component poor ores has locally separate areas of distribution according to field observations. This peculiarity is easily explained by the scheme of deposition stated above.

The view that the two-component poor ores are secondarily derived from the three-component poor ores by oxidation seems to have been entertained almost universally. Yet, the observed distribution of those ores in which finely banded structure is extremely well preserved, like those in An-shan, clearly shows that it is more reasonable to assign this to primary sedimentation factors.

The two-component poor ores may, at a glance, seem to be entirely different from the three-component poor ores. Yet, upon closer observation, the latter ores are known to be the same as the two-component ores, only with another band of iron silicates or of iron carbonate cherts. This is naturally expected from the above-stated conditions of sedimentation. That is, an acid semi-cycle is included in an acid-alkaline complete cycle itself. In fact, the two-component ores of the lake margin of a complete cycle, traced laterally into the lake

center, pass into constituent bands of the three-component poor ores. Consequently it is quite impossible that such two-component ores are derived from three-component ores by a later oxidation. If the oxidation is a necessary procedure, it must have operated "exactly at the same time with the deposition of those thin bands, and that, with a regular intermittent recurrence." Such a syngenetic oxidation, if present, is only one of the sedimentational conditions of well aerated, hence oxidizing, lake water. Thus it coincides with the writer's "acid 1" or "acid 2" stages of sedimentation.

Successive Changes in the Pre-Cambrian Environments, and the Genesis of the Banded Iron Ores

The banded iron ores are distributed, on each continent, only in the Pre-Cambrian rocks and duplicates are not present in later geological systems. On each continent they constitute a great formation, the thickness sometimes reaching over 200 m. Sedimentary iron ore beds in the Paleozoic and Mesozoic groups range from one to several meters thick at their maximum.

That the banded iron ores are the product of mature weathering has already been pointed out by Prof. C. K. Leith. According to the writer's study of the compositions and texture of the banded iron ores it is thought that they are products of an environment of distinct chemical weathering and sedimentation. Other sediments with which the banded iron ores are accompanied also point to the predominance of chemical changes.

Precipitates	Medium of deposition
Aluminous argillite	Acidic
Limestone & dolomite	Weakly alkaline
Chloritic argillite	Alkaline

These fine-grained, compact sediments attain a thickness of around 10,000 m. (17,000 m. at Ta-li-tzu-kou, east Manchuria), and sandy and conglomeratic rocks are of very rare occurrence. These facts point to large-scale chemical changes on one hand, and to very subordinate or negligible mechanical weathering and sedimentation on the other.

Thus, we must accept that such an extraordinary environment obtained only in the Pre-Cambrian era and has never been reproduced in later geologic ages. The Pre-Cambrian

environments of deposition can be divided, at least, into three stages. The characteristic features of these three stages, the nature of original sediments and their metamorphic derivatives may be summarized as follows:

Stage	Environment	Original sediments	Metamorphic derivatives
I.	High temperature hydrothermal (alkaline chemical weathering)	Alkali-bentonite	Gneisses with subordinate schists
II.	Low temperature hydrothermal—cold water (alkaline & acid chemical weathering with subordinate mechanical weathering)	Aluminous argillite, limestone & dolomite, chert, iron hydroxide, iron silicate (chlorite)	Phyllite, mica, schist, chlorite schist, hornblende schist, banded iron ores, ferruginous chert, crystalline limestone, dolomite (magnesite), eulysite, migmatite
III.	Cold water (same as Paleozoic & later) (predominating mechanical weathering)	Sandstone with aeolian rounded desert sands & dreikanter, shale, cherty limestone, glacial tillites	Quartzite, phyllite, cherty limestone, tillite

The sequence of the change of environments is supposed to have been the following:

1st stage:—Water vapor began to condense into hot rain which reached the earth's surface and began to act upon the lithosphere. In the atmosphere were still very large quantities of water vapor and CO_2, HCl and N_2. Consequently the density of the atmosphere was very large and, acting as the so-called heat blanket, it hindered the radiation of the earth's heat as well as that from the sun. As the result of the action of such a high temperature water upon the lithosphere, bentonites or active clays of the montmorillonite family were produced not only from tuffs and lavas but also from every kind of plutonic rocks.

Owing to very rapid decomposition of these igneous rocks, a large quantity of alkalies was set free and the earth's surface was strikingly alkaline. Consequently the bentonites adsorbed much alkali to become alkali-bentonites which showed nearly the same compositions as the parent igneous rocks, *i.e.*, the stage is characterized "sedimentary non-differentiation."

2nd stage:—As the temperature gradually decreased, the speed of the rock decomposition slackened and consequently the amount of free alkali was decreased and owing to the presence of hydrochloric, carbonic and, probably, sulphuric acids, regional acidic environments were introduced for the first time upon the earth's surface, and a small amount of mechanical debris began to be produced.

As the acidic environment was introduced, the bentonites were leached of their alkalies, alkaline earths and later iron oxide, the remnants being changed into aluminous argillite. The soluble salts, either in a true solution or in a colloidal solution, were transported and deposited as chemical sediments.

Thus, at this stage chemical sediments gave rise for the first time to a vast amount of extremely well sorted sedimentary rocks on the earth's surface. The separation of easily soluble from difficultly soluble substances had been carried to its full extent in these rocks, *i.e.*, this stage is characterized by the highest degree of "sedimentary differentiation."

3rd stage:—Dry deserts and cold glaciers made their appearance upon the earth's surface and the environment took on features very close to those of the Paleozoic and later. Consequently mechanical sediments began to predominate.

Thus, in summarizing the characteristics of the original sediments in the Pre-Cambrian era, we can state that at the first stage there appeared non-differentiated clayey products still retaining the compositions of parent igneous rocks; then at the second stage there appeared very well differentiated typical sedimentary rocks of chemical deposits; and lastly at the third stage there appeared the alternation of a large amount of mechanical sediments and minor amounts of chemical deposits such as may be found in the Paleozoic and later ages.

The second stage represents a very long period of time during which the earth's crust, from a low temperature hydrothermal stage, cooled down to a stage similar to the Paleozoic and later ages. Its time duration is thought to be much longer than that of the first and the third stages. The banded iron ores are the product of the predominant chemical weathering and deposition under such a particular environment which obtained only once in the history of the earth's surface, toward the middle of the Pre-Cambrian era.

ACKNOWLEDGMENTS

Since 1940, Mr. G. Asano has published his studies in a series of papers which as a whole makes a comprehensive monograph. His petrographical studies on the banded iron ores in Manchuria are in more detail than any of those of earlier students and, above all, his description of the eulysitic ores and his hints at the progressive metamorphism of the ores are new and instructive.

The writer owes his idea of "ISOSIALS" of the generalized soil profile to the experiments on the isoelectric points of soil colloids by Dr. Sante Mattson of the Agricultural Experiment Station, New Jersey, U.S.A., and to the chemical analyses of clay minerals systematically taken from over 50 meters of a typical lateritic profile at Bintan Island, Netherland East Indies, by Dr. van Bemmelen of the Geological Survey, Bandoeng, Java.

To Prof. C. K. Leith and Prof. W. H. Twenhofel, the writer is indebted for his interest in the Pre-Cambrian and in sedimentation, since 1927-28 when the writer was a student in the Graduate School at the University of Wisconsin. Their addresses and writings have been an inspiration to the writer ever since, and he wishes to express his sincere gratitude to these gentlemen and to his other former professors. To Prof. Twenhofel special thanks are due for giving generously of his time in critical reading of the manuscript.

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THERMAL STUDY OF JAROSITE

J. LAURENCE KULP AND HANS H. ADLER

ABSTRACT. Jarosite, argentojarosite, and plumbojarosite are examined by differential thermal analysis and X-ray diffraction. The structural and chemical changes which these minerals undergo on heating are discussed and compared with alunite.

In general two endothermic peaks at about 400° C. and 700° C. are the major thermal features. The first large endothermic peak is associated with the OH loss and the jarosite structure destruction. This is followed by a small exothermic peak attributed to crystallization of Fe_2O_3 (hematite). The second endothermic peak is due to decomposition of $Fe_2(SO_4)_3$ produced during the jarosite lattice destruction. A number of thermal curves of jarosite group minerals from typical localities are discussed. Substitution is considered from a standpoint of mineral structure and geochemical conditions.

INTRODUCTION

IN recent years application of differential thermal analysis to the solution of mineralogical problems has met with considerable success.

The types of equipment, theory, and use of differential thermal analysis have been reviewed by Speil, Berkelhamer, Pask and Davies (1945), Grim and Rowland (1942), and Kerr and Kulp (1948). The method is applicable to minerals which undergo endothermic or exothermic changes within the limits of the temperature ranges ordinarily covered by available apparatus. Most work has been carried out from room temperature to about 1100°C. but at times higher temperatures have also yielded valuable information.

Although the thermal curves for alunite and jarosite have previously been published, much remains to be said concerning the thermal history, the variations in the thermal curves within the alunite-jarosite group, and the correlation of these phenomena with structure. It is the purpose of this investigation to indicate the typical thermal curve for a number of jarosite minerals, to describe the chemical reactions which produce the characteristic peaks in the thermal curve, and to examine the possible cation substitution.

The minerals of the jarosite group are:

Jarosite	$K_2Fe_6(OH)_{12}(SO_4)_4$
Argentojarosite	$Ag_2Fe_6(OH)_{12}(SO_4)_4$
Plumbojarosite	$PbFe_6(OH)_{12}(SO_4)_4$
Ammoniojarosite	$(NH_4)_2Fe_6(OH)_{12}(SO_4)_4$
Natrojarosite	$Na_2Fe_6(OH)_{12}(SO_4)_4$

Because of the frequency of occurrence, relative economic importance and availability of specimens, the potassium, silver and lead members were studied.

ACKNOWLEDGMENTS

The authors wish to acknowledge the scientific counsel of Professor Paul F. Kerr. They are also indebted to Professor Ralph J. Holmes for many useful suggestions in X-ray diffraction technique.

TECHNIQUES AND PROCEDURE

X-ray diffraction was used to confirm the identity of the samples and to determine the structural changes of the material on heating. Debye powder photographs were taken with iron radiation. The various members of the jarosite group give sufficiently different powder patterns to permit rapid identification.

All specimens were subjected to semi-quantitative chemical analysis using the Curtman (1942) scheme. In table 1 the cations are recorded as major, minor, or trace constituents. Through analysis of samples with known metallic content it is estimated that "major" refers to greater than 5%, "minor" indicates 1-5% and "trace" considerably less than 1%.

The multiple differential thermal analysis apparatus employed is described by Kerr and Kulp (1948). A heating rate of 12.5° per minute up to 1000°C. was used. The material was ground to pass 300 mesh, packed uniformly in the thermocouple well, and heated without covering. This small particle size was found necessary to obtain comparable curves, for, although some of the specimens are reasonably coarse, others are extremely fine powders.

SPECIMEN DESCRIPTION

The specimens studied were obtained from the Egleston Mineral collection of the Department of Geology, Columbia University. In addition, a synthetic jarosite prepared by Professor Paul F. Kerr after the method of Fairchild (1933) for an earlier investigation was available.

The members of the jarosite group show few distinguishing features in hand specimen. All occur as soft masses or aggregates of fine pale-yellow to dark-brown flakes varying in luster.

Optical examination indicated the absence of impurities aside from a small quantity of an opaque red substance found associated with jarosite from several localities. X-ray examination and chemical tests showed it to be quartz coated by goethite. The optical properties of the specimens studied fell within the range recorded in the literature.

In each case the material for thermal analysis was carefully selected for homogeneity.

"Argentojarosite" from Eureka, Utah, "plumbojarosite" from Almada, Mexico, and "plumbojarosite" from Pioche, Nevada, are each composed of both yellow and brown material. X-ray examination indicates the brown material from Almada to be predominantly plumbojarosite, whereas the yellow portion is apparently an intergrowth of plumbo- and argentojarosite. To verify this a 1:1 mixture of argentojarosite from Eureka, Utah, and plumbojarosite from the Eryscian mine, Chihuahua, Mexico, was artificially prepared and an X-ray diffraction powder pattern taken. The pattern obtained was identical to that of the yellow material from Almada, Mexico.

THERMAL HISTORY AND STRUCTURE

The thermal curves of the specimens studied are shown in figure 1. All are characterized by two major endothermic peaks. These are supplemented or modified by the particular chemical constitution of the mineral lattice, intergrown members of the group, and active or inactive impurities.

In order to gain a better understanding of the structural and chemical behavior of these minerals on heating and thereby to interpret the thermal curves adequately, the most typical specimens of jarosite, plumbojarosite and argentojarosite, were heated just past each significant peak, then examined by X-ray methods. For these experiments the following specimens were used: jarosite, Santa Maria mine, Jelardena, Durango, Mexico; plumbojarosite, Eryscian mine, Chihuahua, Mexico; and argentojarosite, Tintic Standard mine, Eureka, Utah.

The thermal decomposition of alunite has already been studied by Fink, Van Horn and Pazour (1931). Since the structures of alunite, $K_2Al_6(OH)_{12}(SO_4)_4$ and jarosite, $K_2Fe_6(OH)_{12}(SO_4)_4$, are similar (Hendricks, 1937), an understanding of the thermal decomposition of alunite facilitates experimentation within the jarosite group. The aluminum or iron

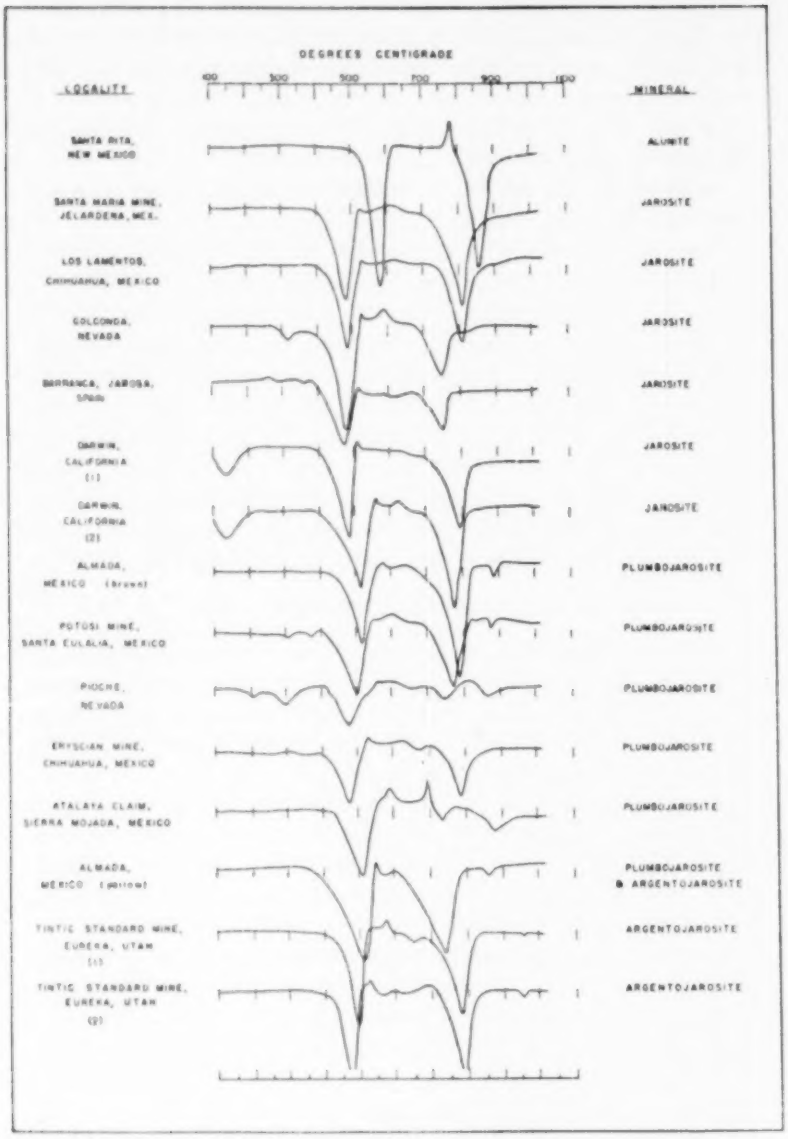

Figure 1. Differential thermal curves of alunite and jarosite specimens.

is surrounded octahedrally by four hydroxyl groups and two oxygen atoms of sulfate groups. Potassium has a coordination number of twelve, and is surrounded by oxygen and hydroxyl groups. The linkage is such that a loss of OH would cause complete decomposition of the structure, and then considerable rearrangement must take place in order to form hematite, ferric sulfate, or other possible residual products.

Fink, Van Horn and Pazour (1931) heated alunite for long periods at various constant temperatures and studied the products by means of X-ray diffraction. Alunite heated 18 to 48 hours from 250° C. to 500° C. gave only sharp lines characteristic of the mineral. Heating for 20 hours at 600° C. produced a diffuse pattern indicating a small amount of $K_2SO_4 \cdot Al_2(SO_4)_3$, while heating for 13 hours at 700° C. gave sharp lines of the potassium aluminum sulfate. At 800° C. alpha-Al_2O_3 lines became evident as did some K_2SO_4 lines, but the potassium aluminum sulfate lines were absent. Heating further to 1000° C. and 1200° C. only sharpened the alpha-Al_2O_3 and K_2SO_4 lines.

The thermal curve of the alunite from Santa Rita, New Mexico (fig. 1) can be readily interpreted in terms of the chemical changes. It should be noted, however, that the dynamic differential heating method produces peaks at somewhat higher temperature than the static equilibrium method used by Fink *et al.* (1931).

The first large endothermic peak occurs at the point of destruction of the alunite lattice according to the equation $K_2[Al_3(SO_4)_2(OH)_6]_2 \xrightarrow{550° C.} K_2SO_4 \cdot Al_2(SO_4)_3 + 2Al_2O_3 + 6H_2O$. The X-ray pattern at 600° C. is diffuse but the faint lines of the alum salt, $K_2SO_4 \cdot Al_2(SO_4)_3$, are discernible. That amorphous alumina is present at this stage is confirmed by the fact that the solution velocity in strong alkali of the mass heated to 600° C. is greater than that of alunite heated to any higher or lower temperature and results in practically complete recovery of alumina. As the temperature is increased to 700° C. the alum crystallization continues and gives sharper X-ray lines while the alumina remains in the amorphous state. The differential thermal curve reveals that the exothermic alpha-Al_2O_3 recrystallization is abrupt and immediately precedes the decomposition, $K_2SO_4 \cdot Al_2(SO_4)_3 \rightarrow K_2SO_4 + Al_2O_3 + 3SO_3$.

Above the second large endothermic peak there is little

change in the structure, but crystal growth continues with increasing temperature. Presumably the heat effect of the crystallization of the Al_2O_3 produced as a result of the decomposition of the alum salt at 800° C. is incorporated into the general endothermic peak.

The thermal history of jarosite from the Santa Maria mine is similar but not strictly analogous to that of alunite. While the structure of the two minerals is essentially the same, the chemical reactions that ensue upon heating are different. The destruction of the lattice occurs about 100° C. lower in jarosite than in alunite. This is probably due to the OH-Fe bond being weaker than the OH-Al bond, which behavior is suggested by the large ionic radius of Fe^{+3}(0.67A°) as compared to Al^{+3}(0.57A°). The decomposition reaction is similar to that of alunite, *i.e.*, $K_2[Fe_3(SO_4)_2(OH)_6]_2 \xrightarrow{460° C.} K_2SO_4 \cdot Fe_2(SO_4)_3 + 2Fe_2O_3 + 6H_2O$ with one significant difference that, whereas the amorphous alumina does not recrystallize until about 780° C., the Fe_2O_3 produced in this decomposition is crystallized directly after the destruction of the jarosite lattice. This is reflected by the small exothermic peak at about 500° C. immediately following the endothermic decomposition. While this small sharp exothermic peak is observable on the Santa Maria mine specimen, it is more clearly developed in most of the other curves. Material heated to the end of the endothermic reaction and cooled quickly gave a diffuse X-ray diffraction pattern indicating the presence of hematite and $K_2SO_4 \cdot Fe_2(SO_4)_3$. Heating the product of the initial decomposition at 500° C. for 17 hours produced sharper lines but otherwise left the pattern unchanged. K_2SO_4 and $Fe_2(SO_4)_3$ were intimately mixed in a 1:1 molecular ratio and heated at 580° C. for several hours. The pattern produced matched the non-hematite lines in the decomposed jarosite. Since the iron oxide had crystallized by 600° C., no further reaction was observed prior to the second decomposition which appeared at about 700° C., *i.e.*,

$$K_2SO_4 \cdot Fe_2(SO_4)_3 \xrightarrow{700° C.} K_2SO_4 + Fe_2O_3 + 3SO_3.$$

The X-ray diffraction pattern of material heated past the second endothermic peak showed only K_2SO_4 and hematite lines. That the endothermic reaction corresponding to the decomposition of $K_2SO_4 \cdot Fe_2(SO_4)_3$ occurs at lower tempera-

tures than that for the $K_2SO_4 \cdot Al_2(SO_4)_3$ in alunite, is also consistent with the structural picture.

A similar experimental procedure with plumbojarosite from the Eryscian mine yielded slightly different results. The decomposition apparently is as follows:

$$Pb[Fe_3(SO_4)_2(OH)_6]_2 \rightarrow PbSO_4 + Fe_2(SO_4)_3 + 2Fe_2O_3 + 6H_2O.$$

The material submitted to X-ray diffraction after the first endothermic peak produced $PbSO_4$ and $Fe_2(SO_4)_3$ lines with an indication of diffuse hematite lines.

The double salt $PbSO_4 \cdot Fe_2(SO_4)_3$ probably does not form due to the difference in the structure of $PbSO_4$ (barite type) as compared with the K_2SO_4 type (Evans, 1939). The "holes" in the plumbojarosite structure resulting from divalent lead ions occupying only half of the possible potassuim ion positions, probably are an additional hindrance to the double salt formation.

At higher temperatures (700° C.) the $Fe_2(SO_4)_3$ breaks down into hematite and sulfur trioxide leaving a residue of Fe_2O_3 and $PbSO_4$ at 1000° C., which was confirmed by X-ray diffraction examination.

The argentojarosite (Tintic Standard mine) apparently decomposes in still another way. Due to the instability of Ag_2SO_4 at the temperature of argentojarosite decomposition, the following reaction is postulated:

$$2Ag_2[Fe_3(SO_4)_2(OH)_6]_2 \rightarrow 4Fe_2O_3 + 2Fe_2(SO_4)_3 + 4Ag + 12H_2O + 2SO_3 + O_2.$$

The loss of oxygen is expected as the decomposition temperature of Ag_2O is only 300° C. X-ray diffraction patterns of the material heated just past the first endothermic peak produced much more diffused lines than patterns taken after similar treatments to jarosite or plumbojarosite. Faint diffuse lines of hematite and $Fe_2(SO_4)_3$ were detected. No lines corresponding to Ag_2SO_4 were present. The absence of Ag_2SO_4 at 500° C. is indicated by two other facts. First, there is no other peak which would indicate the breakdown of Ag_2SO_4 up to its decomposition temperature at 652° C. Second, the corrosion of the nickel specimen holder is more intense than that observed after decomposing jarosite or plumbojarosite. This indicates the release of SO_3 in the presence of water vapor during the breakdown of the argentojarosite lattice.

Again at about 800° C. the $Fe_2(SO_4)_3$ decomposes into Fe_2O_3 and SO_3. The high temperature product in this case is primarily hematite and some metallic silver. The presence of this metal is shown by the endothermic peak at about 950° C. The melting point of pure silver is 960.5° C. It was found that this peak was reversible and that with each successive melting it lost some of its amplitude. This would occur if the silver gradually distilled into cooler parts of the apparatus.

From this information it is to be expected that the ammonio- and natrojarosite thermal curves will show similar characteristics. The $(NH_4)_2SO_4$ produced in the ammoniojarosite decomposition should volatilize immediately, leaving again hematite and $Fe_2(SO_4)_3$. The ammoniojarosite curve should therefore resemble the argentojarosite curve minus the 950° C. endothermic dip.

The natrojarosite may more closely resemble potassium jarosite in its thermal history, Na_2SO_4 remaining at 1000° C. Whether a double salt $Na_2SO_4 \cdot Fe_2(SO_4)_3$ would form is questionable. While the Na_2SO_4 structure is more similar to that of K_2SO_4 than to $PbSO_4$, it is nevertheless different and that difference may be enough to make the double salt formation energetically unfavorable.

Natroalunite would be expected to follow the alunite decomposition pattern closely except again for the possible absence of double salt formation. The double salt formation has relatively little effect on the thermal curve since it decomposes at only slightly higher temperatures than pure aluminum sulfate. This can be ascribed to the displacement of the equilibrium,

$$K_2SO_4 \cdot Al_2(SO_4)_3 \rightleftharpoons K_2SO_4 + Al_2(SO_4)_3 \rightleftharpoons K_2SO_4 + Al_2O_3 + 3SO_3.$$

THERMAL ANALYSIS CURVES

The thermal curves of the specimens studied in the temperature range 100-1000° C. are shown in figure 1. Table 1 gives the summary of the critical chemical and X-ray data.

The curve of the Santa Rita, New Mexico alunite has been fully discussed in the foregoing section. The jarosite from the Santa Maria mine gives a thermal curve with no evidence of foreign constituents. Chemical analysis indicates a trace of lead which does not appear to affect the thermal curve to any appreciable extent. The high-purity jarosites show at least

TABLE 1

Locality	*Mineral* (based on X-ray data)	*Chemical Data* *Pb*	*Ag*	*K*	*Al*	*Fe*
Santa Maria mine, Jelardena, Mex.	Jarosite	trace	X	major	X	major
Los Lamentos, Chihuahua, Mex.	Jarosite	trace	X	major	X	major
Golconda,* Nevada	Jarosite	——	—	——	—	——
Barranca,* Jarosa, Spain	Jarosite	——	—	——	—	——
Darwin, (1) & (2) California	Jarosite	X	X	minor	—	major
Almada, (brown) Mexico	Plumbojarosite	major	trace	X	X	major
Potosi mine, Santa Eulalia, Mex.	Plumbojarosite	major	trace	X	X	major
Ploche, Nevada	Plumbojarosite	major	——	X	X	major
Eryscian mine, Chihuahua, Mex.	Plumbojarosite	major	X	X	X	major
Atalaya claim, Sierra Mojada, Mex.	Plumbojarosite	major	X	X	minor	major
Almada, (yellow) Mexico	Plumbojarosite and Argentojarosite	major	major	X	X	major
Eureka, (1) & (2) Utah	Argentojarosite	X	major	X	X	major

—— not determined
X not detected

* These specimens were subjected to X-ray examination during the course of previous investigations undertaken by Professor Paul F. Kerr and were used in this study for comparison purposes only.

two significant differences to the plumbojarosites. First, the initial decomposition begins at a slightly lower temperature, *e.g.*, most of the jarosite specimens start decomposition from 370-400° C., while practically all of the plumbojarosite and argentojarosite specimens start decomposing about 400° C. and above. A second difference is found in the temperature of the second endothermic peak. Here the jarosite is consistently higher, ranging from 810-820° C., in the high-purity specimens. The Golconda and Barranca specimens contain appreci-

able impurities as shown by X-ray patterns and the small amplitude of the thermal peaks. Plumbo- and argentojarosite give this high temperature endothermic peak about 780-790° C. It can also be seen that the latter minerals tend to start this final $Fe_2(SO_4)_3$ decomposition at a lower temperature. The double salt formed during the decomposition of jarosite apparently increases the stability of the ferric sulfate.

The Los Lamentos jarosite is similar to the Santa Maria specimen discussed above.

The Golconda and Barranca specimens yield typical curves. The $Fe_2(SO_4)_3$ decomposition peaks, however, occur at somewhat lower temperatures due to the presence of impurities. The Golconda specimen shows the presence of goethite in the 240° C. endothermic peak and may contain siderite along with some inert impurity.

The Darwin jarosite is not homogeneous. A sericite-like material is present which may produce the slight lowering of the high temperature endothermic peak.

The Almada plumbojarosite (brown) shows the presence of a small endothermic peak at 885° C. indicating a small amount of admixed argentojarosite. The X-ray diffraction pattern shows several faint lines of argentojarosite. It appears impossible to entirely separate this brown material from the yellow in hand specimen. The yellow material apparently contains a high percentage of argentojarosite.

The Potosi mine plumbojarosite has considerable impurities associated with it. The endothermic dips prior to the main decomposition are due to goethite and possibly some sulfide. The 875° C. endothermic peak is attributed to the melting of silver derived from the decomposition of admixed argentojarosite. The X-ray pattern of the Potosi specimen confirms the presence of argentojarosite.

The Pioche specimen appears to have considerable inert impurity, thus lowering the amplitude of the peaks. Some evidence of a clay mineral of the montmorillonite group is suggested. The high temperature peak is lowered due to dilution and the 863° C. peak may be the decomposition of a small quantity of $Al_2(SO_4)_3$, either derived from mixed alunite or substituted Al in Fe positions in the jarosite.

The plumbojarosite of the Eryscian mine appears to be of reasonable homogeneity and purity as indicated by X-ray and chemical information. This curve has already been discussed.

The plumbojarosite from the Atalaya claim is of considerable interest in that it is apparently a case of substitution of Al for Fe in the jarosite lattice. The X-ray diffraction pattern shows a shift in several strong lines toward the alunite spacings. An aluminum-substituted member of the jarosite group is to be expected on theoretical grounds but has not been previously reported. The chemical analysis indicates the presence of aluminum. The thermal curve can be interpreted most reasonably as that produced by an aluminum-substituted plumbojarosite. During the initial decomposition, amorphous Fe_2O_3, Al_2O_3, and crystalline $PbSO_4$, $Fe_2(SO_4)_3$ and $Al_2(SO_4)_3$ are formed. The Fe_2O_3 crystallizes at slightly higher temperatures to hematite and the amorphous Al_2O_3 goes over to alpha-Al_2O_3 at 692° C., followed rapidly by the ferric sulfate decomposition (733° C.). The final endothermic peak at 874° C. is presumably due to the final $Al_2(SO_4)_3$ decomposition.

The Almada, Mexico yellow material begins decomposing at a temperature near that of jarosite. The reason for this anomalous behavior lies in the extremely fine particle size of this specimen. X-ray patterns show the yellow material from Almada to be a mixture of plumbojarosite and argentojarosite in roughly equal concentrations. The small endothermic peak (950° C.) characteristic of the presence of metallic silver is also present. The two argentojarosite specimens from the Tintic Standard mine are similar and may be considered typical of the mineral.

In summary—the thermal characteristics of the jarosite group are such that the presence of thermally active or inactive impurities can be readily detected. Also, if the material is monomineralic, the particular member of the jarosite group is identifiable from the thermal curve. Furthermore, argentojarosite can be detected in intimate intergrowths by the presence of the 900-950° C. melting peak for silver. The potassium jarosite differs from the lead and silver varieties by having a lower temperature for the initiation of the lattice destruction and a higher temperature for the second endothermic peak.

SUBSTITUTION

Theoretically a number of possibilities exist for substitution in the jarosite group. The structure is composed of three main cation positions which in ordinary jarosite are occupied by potassium, iron, and sulfur. The possible replacements based on ionic radii (Palache *et al.*, 1944) are shown in table 2.

TABLE 2

Potassium position		Iron position		Sulfur position	
Ion	Ionic Radii	Ion	Ionic Radii	Ion	Ionic Radii
*Na^{+}	0.98 A°	*Fe^{+3}	0.67 A°	*S^{+6}	0.29 A°
*K^{+}	1.33	*Al^{+3}	0.57	*P^{+5}	0.34
**Rb^{+}	1.48	Cr^{+3}	0.65	As^{+5}	0.47
*Ag^{+}	1.20	Co^{+3}	0.65		
*Pb^{+2}	1.32				
Sr^{+2}	1.18				
Ba^{+2}	1.36				
Ca^{+2}	1.01				
Au^{+2}	1.37				
Hg^{+2}	1.11				
**Ce^{+3}	1.10				

* These cations form known jarosite-alunite minerals.

** These cations form synthetically prepared jarosites (Fairchild, 1933).

The wide range of ionic radii possible in the potassium position is attributed to the relative openness of the structure.

The extent to which substitution is found in these minerals will be determined in large measure by the geochemical environment present during their formation regardless of the substitution theoretically possible. As Hendricks (1937, p. 783) points out, "There is no explanation in the structure for the observation that the various minerals are usually found free of extensive isomorphous replacement."

In this study none of the samples indicates substitution for the sulfate group by either phosphate or arsenate. The substitution of aluminum for iron has been indicated in the specimen from the Atalaya claim and may be present in the Pioche specimen to a lesser extent. No other substitution has been demonstrated. It is entirely conceivable, however, that a chromium jarosite could be formed, if a unique combination of potash-iron-acid-bearing solutions passed through a chromite deposit. The probability of such an unusual set of conditions is so small that it accounts for the absence of this mineral. Complete substitution in the potassium positions by other cations gives rise to the various jarosite minerals. It is interesting to note that analyses in the literature seldom reveal the presence of more than one of the potassium position cations in a single specimen. In the present study partial substitution of silver or lead in jarosite, or of silver in plumbojarosite, and lead in argentojarosite, has not been observed. The one or two plumbojarosite specimens that do give evidence for the pres-

ence of silver probably contain a small quantity of argentojarosite. The striking absence of substitution is evident from X-ray diffraction patterns in the case of the yellow material from Almada, Mexico. Since both argentojarosite and plumbojarosite are indicated the most reasonable interpretation is the existence of two generations. Because of the low temperature of formation and relative insolubility in dilute acids, it is to be expected that once jarosite has formed in one geochemical environment, any change in the composition of the solutions with regard to the potassium-substituting cation (either Ag or Pb) will not rework the member already formed but simply deposit the new member. Apparently this is the case with the Almada material and may be the situation in the Potosi specimens. In view of the relative solubilities and the sources of lead-bearing as against potash-bearing solutions, it is not too likely that potassium and lead would be present in roughly equal concentrations at the time of formation of the jarosite mineral. As long as the concentrations differed by as much as a 1:20 ratio no appreciable substitution would be detected by inspection of thermal curves or X-ray patterns.

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FOSSIL CUP CORALS FROM THE METAMORPHIC ROCKS OF CENTRAL VERMONT*

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ABSTRACT. Cup corals are herein reported, from phyllite that is interbedded with the crystalline limestones of the Waits River formation, at several localities in central Vermont. The corals, preserved chiefly as silica replacements 1.5±cm. in diameter, are clustered along bedding zones. They are oriented parallel to crenulations in cleavage that cuts across the bedding. A central vesicular zone, septa, and a circumferential wall are distinguishable in the better preserved coral specimens. V. J. Okulitch reports that the corals are probably *Streptelasma*, possibly *S. corniculum* and that therefore they suggest a Middle Ordovician age. This correlation is partly consistent with meager information already at hand, but may be subject to revision as more data become available.

INTRODUCTION

IN June, 1947, while mapping the Montpelier quadrangle in connection with U. S. Geological Survey investigations of talc deposits in Vermont, the writer discovered cup corals at several localities near the city of Montpelier, and also in East Montpelier and Calais townships. These fossils are remarkable for their preservation in phyllite, and are also a rare find in central and eastern Vermont. At the suggestion of Dr. J. B. Reeside, Jr., of the Geological Survey, they were sent to Professor V. J. Okulitch of the University of British Columbia for identification and age determination. The writer is grateful for Professor Okulitch's report quoted here. It is believed that the mode of occurrence of the fossils will be of interest to structural and metamorphic geologists as well as to paleontologists and stratigraphers.

The writer is indebted to C. G. Doll, P. E. Hotz, R. H. Jahns, J. F. Murphy, Professor Okulitch, and Dr. Reeside for critical reading of the manuscript.

PREVIOUS WORK

The rocks that contain the fossils were originally included in the "calcareo-mica schist" of C. B. Adams (1845, pp. 49, 62), later designated the "calciferous mica schist" by Edward Hitchcock, Sr., who described them in the Report on the Geology of Vermont (Hitchcock, *et al.*, 1861, pp. 475-488).

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Subsequently, C. H. Richardson (1898) proposed the name *Washington limestone* for the more calcareous portion of the "calciferous mica schist," but, finding that this name was preoccupied, he later (1906, pp. 86-90, 115) replaced it with the term *Waits River limestone*. Currier and Jahns (1941, p. 1491) have revised the term "Waits River limestone" to *Waits River formation* to accommodate more correctly the phyllite and other noncalcareous rocks that are abundantly represented in the section.

The various publications of Richardson in the Reports of the Vermont State Geologist have indicated that the "Waits River limestone" is fairly continuous from north to south through the state of Vermont. C. G. Doll and the writer jointly have traced the Waits River formation northward across the International Boundary into the Tomifobia slates and limestones (Clark, 1934, pp. 11-12; Ambrose, 1943) of southern Quebec; H. C. Cooke[1] identifies the Tomifobia formation with the St. Francis series found farther to the northeast in Quebec. Richardson (1898) traced the "Waits River limestone" southward into Massachusetts where the Conway schist (Emerson, 1898, pp. 183-201), contains similar limestone strata. The stratigraphic and structural relationships of the Waits River formation to the Northfield slate and successively older formations to the west have been indicated by Currier and Jahns (1941, pp. 1490-1506). The relationships of these formations to the Gile Mountain formation and associated younger rocks, commonly found to the east, have been noted by C. G. Doll (1945, pp. 16-19).

The Waits River formation and its equivalents in Quebec and Massachusetts have been given age assignments that range from Ordovician to Devonian. Faunal investigations have furnished inconclusive and partly conflicting results, probably inasmuch as the fossil material necessarily is poor because of its occurrence in metamorphic rocks. Currier and Jahns collected fragments of crinoid stems believed to be of "Middle Ordovician or later age" from strata that underlie the Northfield slate (1941, pp. 1501-1502). Richardson (1916, pp. 142-145; 1919, pp. 49-51; Richardson and Camp, 1919, pp. 114-115) reported graptolites from the Northfield slate and Waits River formation, specimens that are believed by Ruedemann

[1] Oral communication, 1949.

(1947, p. 63) to be of both Deepkill and Normanskill age. Doll (1943a) reported crinoids and other forms, which he believes to be of Silurian or possibly Devonian age, from the "Waits River limestone" of northern Vermont and in beds that he assigns[2] to the upper part of the Waits River formation. He reported also a brachiopod, which he believes to be of Lower Devonian age (1943b), from the Gile Mountain formation (1945, p. 19). Poorly-preserved fossils have been reported from a few other areas in the vicinity of the Waits River formation (Richardson, 1902, p. 94; 1929, p. 245; Richardson and Maynard, 1939, p. 96); they furnish no conclusive evidence as to age, and their exact stratigraphic or geographic positions were not recorded or are uncertain. T. H. Clark reports graptolites with "a Trenton aspect"[3] from the Tomifobia formation in Quebec. The St. Francis series of Quebec is reported to contain graptolites of Normanskill age (Cooke, 1937, p. 42). The Conway schist in Massachusetts contains rust-coated cavities that were believed by B. K. Emerson (1898, pp. 200-201) to represent indeterminate fossils.

GEOLOGIC SETTING

The strata in which the corals were discovered form part of the east limb of the Green Mountain anticlinorium, whose axis is coincident with the summit ridge of the Green Mountains about 17 miles to the west. The known fossil localities occur in a belt approximately 2 miles wide that trends north-northeast for about 7 miles from the Winooski River in and east of the city of Montpelier to the vicinity of Bliss Pond in Calais township (fig. 1). This belt parallels the strike of the Waits River formation. The western border of the belt is commonly a little less than half a mile east of the Northfield slate and immediately east of the outcrop of a zone, in the lower portion of the Waits River formation, that is relatively rich in syngenetic pyrite. The average dip of the strata is about 75° W., and both cleavage-bedding relationships and orientation of the corals indicate that in the majority of exposures the tops of the beds face east. Thus the strata are overturned but probably not repeated to an appreciable extent. Discounting repetition, the lowest of the coral-bearing strata are estimated to be

[2] Oral communication, 1949.
[3] Written communication, 1949.

2,000 to 3,000 feet above the base of the Waits River formation, and the fossil zone itself is probably at least 10,000 feet thick. Its eastern (upper) limits have not been determined.

Seven collections were made from the following localities (fig. 1):

1. Montpelier city, 1.35 mi. S. 54° E. of the State House; ledges north of railroad and in line with dam in the Winooski River.

2. East Montpelier township, 0.3 mi. S. 45° W. of school house at East Montpelier Center; east face of ledge about 100 feet west of road.

3. Calais township, 0.8 mi. S. 30° W. of site of No. 7 School; east face of ledge about 200 feet west of road.

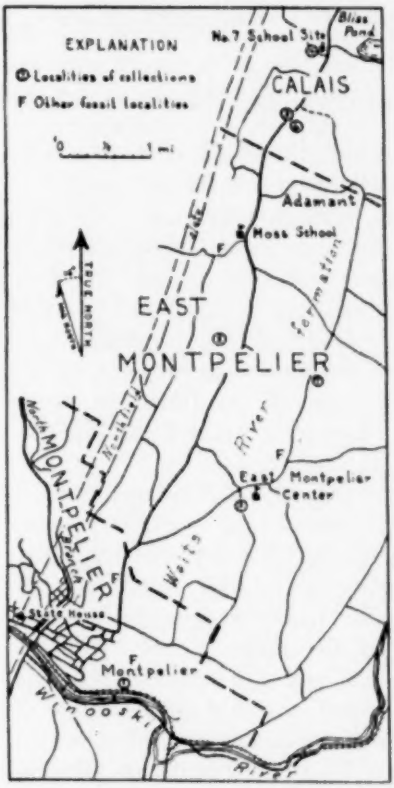

Fig. 1. Index map showing fossil coral localities, Montpelier, East Montpelier, and Calais, Vermont.

4. Calais township, 0.1 mi. due west of site of No. 7 School; at east foot of wooded ledge southwest of bend in road (fossils found in loose fragments).

5. East Montpelier township, 1.1 mi. S. 8° W. of Moss School and about 1,500 feet west of road, within edge of woods near southwest corner of pasture; eastward facing ledge a few feet west of granitic sill.

6. Calais township, 0.85 mi. S. 22° W. of site of No. 7 School and about 400 feet east-southeast of road near center of partly wooded pasture; eastward facing exposure is a few feet west of granitic sill.

7. East Montpelier township, 1.35 mi. N. 28° E. of school at East Montpelier Center and about 300 feet east of road in pasture a little south of fence; east face of ledge.

PETROGRAPHIC AND STRUCTURAL RELATIONS

The rock in which the fossils are commonly preserved is a dark phyllite composed chiefly of sericite and very fine-grained quartz, small amounts of chlorite, and scattered ilmenite plates that are visible to the naked eye. The sericite flakes have a common orientation and form a schistosity parallel to which the cleavage is developed. Crystalline limestone, interbedded with the phyllite, is iron gray on fresh surfaces, but weathers to a brown earthy crust. About one-half to two-thirds of the volume of the limestone is calcite, and the remainder is composed of quartz and minor quantities of muscovite.

Bedding may be traced most favorably where the cleavage crosses it at a relatively high angle and where the fossils, or syngenetic sulfides, distributed parallel to the beds, have preserved stratification as fossiliferous or rusty zones. Bedding is best seen at contacts between the phyllite and the limestone.

The texture of the rocks of the Waits River formation coarsens to the east, and also locally in the vicinity of granitic sills. Near the latter, increased metamorphic effects are quite apparent, particularly the appearance of spotted phyllite with porphyroblasts of biotite and cordierite. The limestone may be whitened and may contain considerable quantities of diopside and titanite.

The near-vertical east faces of phyllite ledges commonly coincide with the planes of bedding, and the cleavage dips westward into these faces at gentler angles (plate 1, fig. 1; text fig. 2). These relations characterize most of the fossil localities. A lineation, formed by fine crenulations in the cleavage, plunges northward in the plane of the cleavage (plate 2, fig. 1; text fig. 2). The calyces of the corals open out easterly at the bedding plane in the direction of the stratigraphic tops of the beds, and taper downward in the plane of the cleavage in such a way that the long axes of the individuals are parallel to the lineation. The corals are commonly flattened in the plane of the cleavage, which parts around them and gives them an eye-like appearance. There is some megascopic evidence that the corals have been rotated; the cleavage that adjoins a few of the individuals forms a helical pattern adjacent to the fossils (plate 2, fig. 1). Too few occurrences of this feature have been observed to indicate whether or not adjacent corals, presumably in a common structural setting, have been rotated in the same direction.

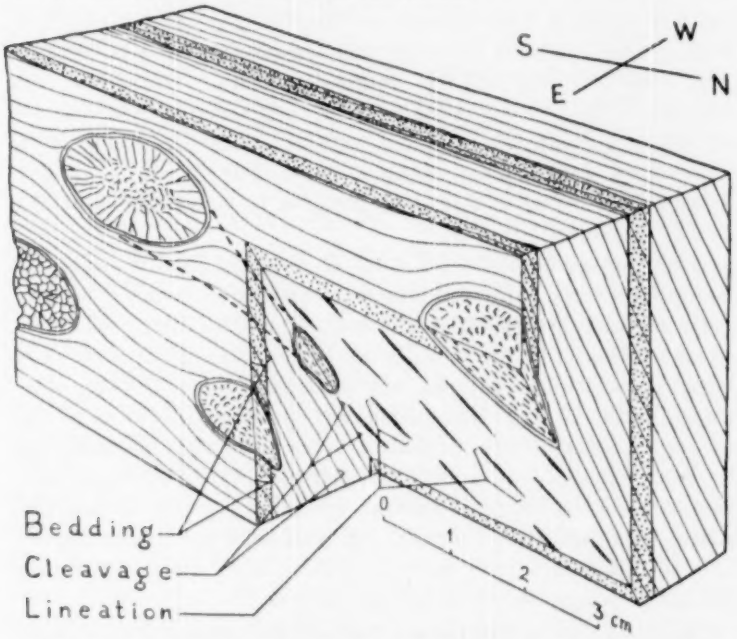

Fig. 2. Block diagram showing the relationship of the fossil corals to bedding, cleavage, and lineation.

The structural relationships indicated by data recorded at the locality of collection No. 7 are typical of most exposures of the Waits River formation in the Montpelier - East Montpelier - Calais belt:

Bedding	Cleavage	Lineation
Strike N. 17° E.	Strike N. 23° E.	Bearing N. 21° W.
Dip 88°W.	Dip 50° W.	Plunge 40°

The strikes of bedding and cleavage are commonly within 10 degrees, as shown here, and are parallel at many localities.

FOSSIL DESCRIPTIONS

The best-preserved corals (plate 1) are those at the locality (fig. 1) from which collection No. 7 (plate 2) was obtained. Hundreds of individuals are exposed on the nearly vertical east face of a ledge that is more than 75 feet long and stands 4 to 5 feet above the pasture. The petrographic and structural relationships of the fossils at this locality are similar to those at other localities. Preservation is related to silicification along comparatively open bedding joints and associated partly calcareous zones. The corals are completely replaced by silica, part of which is iron-stained, and most of the calyces are filled with granular quartz that obscures the fossils. The silicification and quartz filling of the originally calcareous corals are believed to have favored their great resistance to deformation, as compared with the adjacent phyllite. Some individuals show only silica replacement, without development of the quartz filling. From them it has been possible to determine that the fossils are actually corals.

The average corallite is 1.5 cm. in diameter, and is estimated to be 2 to 3 cm. long; its length commonly is difficult to estimate because the greatest amount of silicification, and hence preservation, is in the vicinity of the calyces. The basal portions, distal to the calyces, are delimited with difficulty. Distinguishable in the best-preserved specimens, in which the calyces are not filled with quartz, is an outer zone of radiating septa terminated outwardly by a circumferential wall and connected inwardly with a central vesicular zone in which the septal arrangement is lost. The septa of some specimens appear to bifurcate toward the circumferential wall. Professor Okulitch reports on the fossils as follows:

"Some of the specimens are undoubtedly cup corals, others show nothing but a reticulated or vesicular mass. The preserva-

tion is such that all finer details of septa, walls, and the central vesicular zone are lost. Some of the apparent structures are in all probability secondary due to partial recrystallization and solution. I do not think that it would be prudent to give the specimens a definite and precise generic and particularly specific name. But considering their size, number and arrangement of septa, and the presence of a somewhat indefinite central vesicular zone, my impression is that the corals are probably *Streptelasma*. The genus *Streptelasma* is very common in the Middle and Upper Ordovician of North America. If the specimens are *S. corniculum*, as appears likely, the age could be from Black River to the top of the Trenton. I do not think that polishing or sectioning of the specimens would give much additional information. As it is, natural weathering gives a three dimensional aspect of their internal structure."

CONCLUSIONS

Satisfactory correlation of the Waits River formation with the stratigraphic sections of other areas must await further field studies and paleontologic data. The Middle Ordovician age suggested by Professor Okulitch is rather consistent with the meager fossil evidence already available and briefly summarized in the forepart of this paper. In view of the poor state of preservation of all fossils thus far reported, as well as of those collected by the author, it should be recognized that future discoveries of fossils, or of new stratigraphic and structural relations, could result in changes in age assignments.

The author is extending the stratigraphic studies of the formations beneath the Waits River formation initiated by Currier and Jahns (1941), and expects to search for additional fossils in the Waits River formation as time permits. Continued search should result in the discovery of fossils that are as well or even better preserved than those already found. All but one of the collections listed were obtained in the course of but one month of routine geologic mapping and several other coral localities (fig. 1) were observed during this period. The area of discovery was restricted to the part of the Waits River formation that lies within the Montpelier quadrangle. Additional search within this quadrangle, as well as in adjoining areas, seems justified.

PLATE 1

Outcrop of phyllite showing fossil cup corals.

Fig. 1. Bedding-cleavage relationships. The hammer handle is in the projected plane of the bedding surface over which the fossils are scattered; the cleavage, which strikes nearly parallel to the bedding but dips into the face of the outcrop, shows on the surface of the cross-joint on the left.

Fig. 2. Close-up view of the bedding surface. The position of the individual corals is indicated by white quartz that fills the coral calyces; a small coral without the quartz filling is directly in line with the 10¾ inch mark on the foot rule. Two poorly defined joints that pass across the upper half of the view are nearly parallel to the cleavage.

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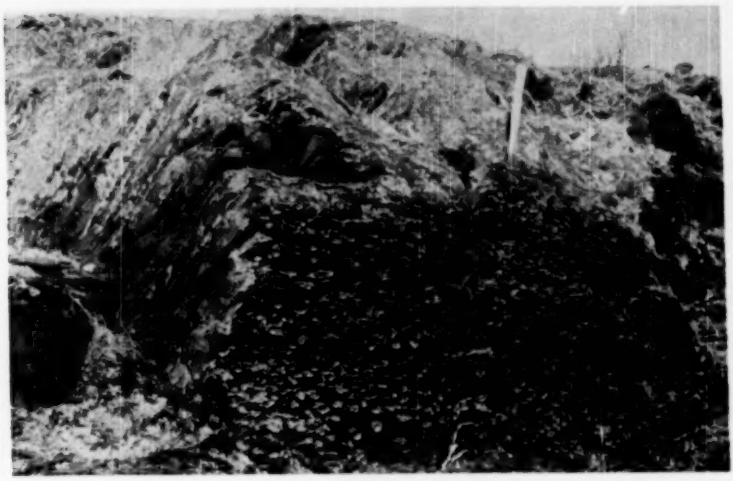

FIG. 1

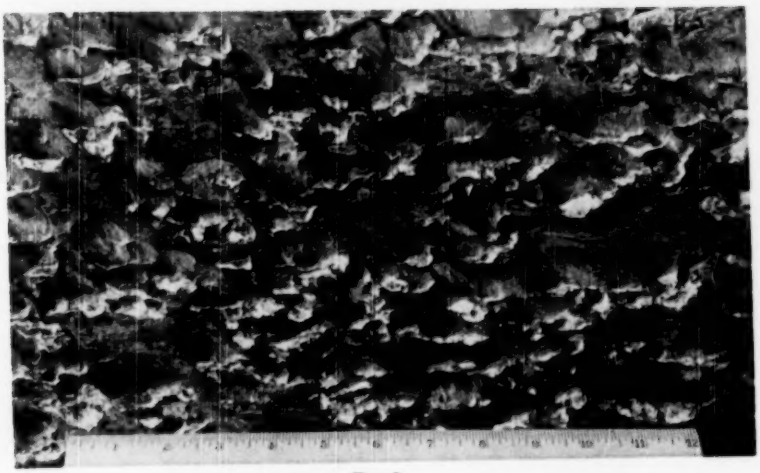

FIG. 2

FIG. 1

FIG. 2

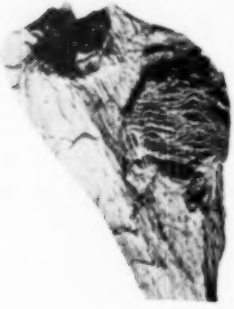

FIG. 3

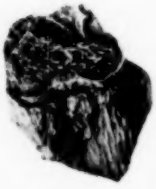

FIG. 4

FIG. 5

FIG. 6

FIG. 7

FIG. 8

PLATE 2

Detailed full-size views of the cup corals.

Fig. 1. In place in the phyllite. Two corals, the upper portions of which are exposed in the plane of the bedding, taper downward and to the right into the specimen and parallel to crenulations in the cleavage. The helical pattern of the cleavage around the upper individual suggests that it has been rotated counterclockwise. Both individuals show a central vesicular zone, radiating septa, and circumferential wall.

Figs. 2-4. In cleavage fragments of phyllite. These specimens were removed from the outcrop by sliding them out parallel to the lineation; they taper downward, and the cross section of a cleavage fragment, which is eye-shaped in the vicinity of the calyx of the coral, flattens out to a spade-shape near the base. Flattening in the plane of the cleavage is particularly evident in figures 2 and 4. The central vesicular zones are relatively large, and the septa are not as well defined as in figure 1.

Figs. 5-8 — Top views.

5. A coral partly fills a hollow within a cleavage fragment.

6. The central vesicular zone commonly forms a protuberance, as shown in this specimen.

7. The septa in this specimen are absent or poorly formed, and the vesicular zone extends to the circumferential wall.

8. Some of the septa in this specimen seem to bifurcate toward the circumferential wall.

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CLIMATIC FLUCTUATION, A SUGGESTED MEANS FOR THE DEVELOPMENT OF LAKE TERRACES, KUNMING BASIN, CHINA

BENJAMIN A. TATOR

ABSTRACT. The tectonic lake basins of Yunnan Province, southwestern China, contain lake terraces the origin of which appears to be related to climatic fluctuation during the Quaternary. The Kunming Basin, containing Lake K'un-yang, was formerly enclosed but has since been included in the Yangtze drainage system by stream capture. The lake terraces were produced by an alternation of deposition and erosion controlled by variations in rainfall during the Pleistocene intervals. The more arid intervals provided an excess of coarse debris which, by clogging the lake outlet, caused temporary stabilization of the lake level. Deposition of terrace materials on the basin floor resulted. Subsequent increase in precipitation, however, allowed the lake outlet to clear away the alluvial dam and the lake level was lowered. Repetition of this cycle under the influence of continuous regional uplift developed terraces at successively lower positions within the basin.

INTRODUCTION

Location

THE Kunming Area includes a large intermontane basin and its bordering highlands in eastern Yunnan Province, southwestern China (figs. 1 and 2). It is one of a number of similar basins of tectonic origin characteristic of Yunnan, the majority of which were occupied by lacustrine waters during relatively recent geologic past. The Kunming basin still retains a portion of its original water body in Lake K'un-yang. Other lakes, including Fuhsien Hai, Yang-tsung Hai, and Chilu Hai are present in smaller basins located east and south of the Kunming basin.

The rugged topography of Yunnan Province places mountain barriers and deep, often impassable valleys across all approaches to the Kunming Area. Adequate communication with surrounding regions has never been achieved. Deeply dissected mountainous terrain separates the basin from the Yangtze Kiang 80 miles to the north. The Burma border lies about 250 miles to the west, the topography in this direction becoming increasingly mountainous and culminating in the southward continuation of the Himalaya arc along the valleys of the Salween and Mekong rivers. The French Indo-China border is located 150 miles to the south, the surface in this

direction being dissected by a maze of deep canyons. The distance from the Kunming Area to the French Indo-China coast is approximately 400 miles.

Climate

The climate is a subtropical monsoon type, the controlling factor being altitude rather than latitude (Jen, 1948). The lake basin stands at 6400 feet, this elevation producing a more temperate climate than is normal for this latitude in Asia. According to Cressey (1934, pp. 373-374) the average minimum temperature is 4° C. and the average summer maximum is 26° C. Seasons are based on wet and dry contrasts rather than temperature differences. Torrential storms occur from May through October, accounting for most of the yearly average precipitation of approximately 40 inches. Strong southwesterly winds characterize the dry winter months and produce local duststorms where moisture and vegetation are scanty. Some believe these storms to have been active in the topographic development of the basin areas since late Tertiary (Brown, 1914). The advent of cold, arid conditions in the Asiatic interior during the Pleistocene is thought to have increased wind activity in Yunnan. A further inference is that the alternation of wind and water action during the dry and wet seasons has been largely responsible for the thick section of fine and coarse clastics which underlies the basin floors.

PHYSICAL SETTING

Topography

The Kunming basin is an elongate, lacustrine plain with dimensions of approximately 35 miles in a north-south direction and a width of 10 to 12 miles (fig. 1). Lake K'un-yang, approximately 25 miles long and 5 to 7 miles wide, occupies the western half of this plain. The surrounding country is prevailingly mountainous, rising to 8000 feet in some localities, and with the relief reaching 2000 feet. The basins and intervening mountains show a definite northeast-southwest alignment. One particularly high ridge parallels the western edge of Lake K'un-yang, presenting a precipitous escarpment known locally as the Sin Chang Cliffs (fig. 1 and plate 2, fig.

2). A broad alluvial flat, barely above the present lake level, intervenes between the lake and the mountainous country to the north, east and south (plate 1, fig. 2). Several alluvial terrace remnants occur at elevations from 10 to 100 feet above the present basin floor along its eastern side.

Drainage

The basin is drained from the southwestern portion by the P'u-to Ho, tributary to the Yangtze Kiang (fig. 1). This single outlet passes through the high Sin Chang Cliffs in a deep, narrow valley. The direction of flow of this stream is first northwestward and then northward to the Yangtze Kiang. Other, more minor streams, dry during much of the year, drain into the basin from the surrounding highlands. Solution activity in the uplands has produced a near-karst topography in many localities.

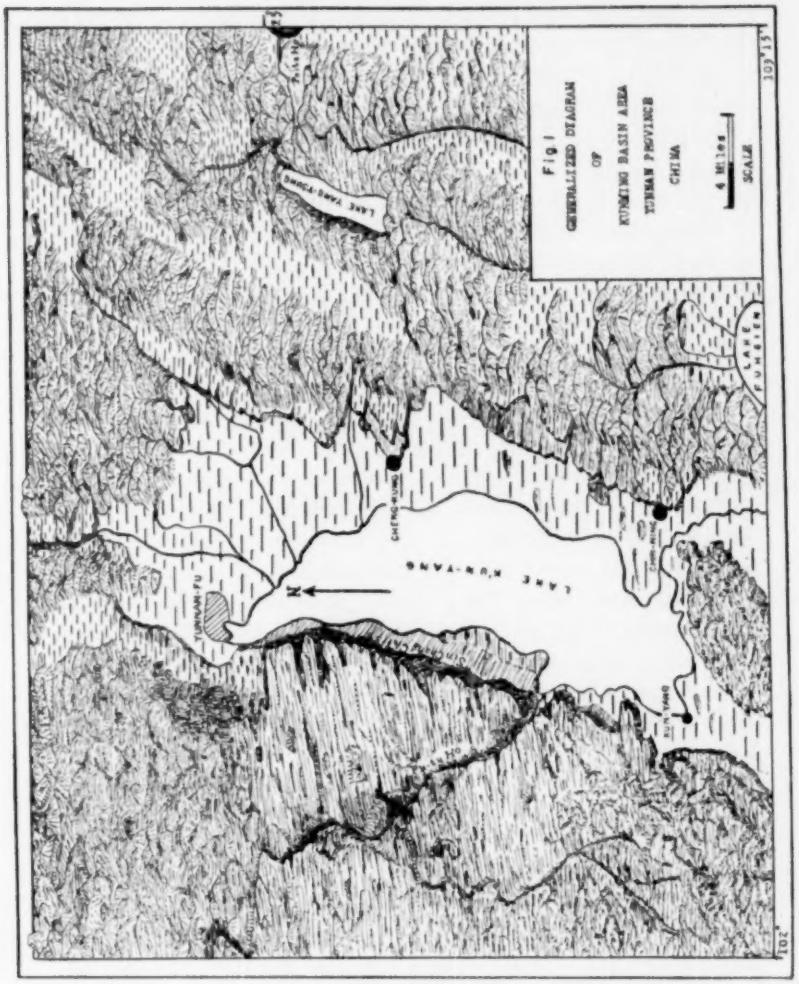
A major drainage divide follows the crests of the ridges east, south, and west of the basin. The runoff east and south of this divide reaches the Peita Ho, tributary to the Hung-shui Kiang (fig. 1). Yang-tsung Hai, Fuhsien Hai, and Chilu Hai drain into the Pieta Ho. The drainage west of this divide is southward into the Yuan Kiang system. Within the basin the runoff is northward into the Yangtze Kiang via the P'u-to Ho, as mentioned above.

An outstanding relief characteristic is the great depth and narrowness of the stream valleys. The P'u-to Ho flows in a precipitous canyon, 2000 feet deep in places. At its juncture with the Yangtze Kiang, relief is in excess of 8000 feet. Minor valleys are also deep and narrow.

It is quite apparent that thorough integration of the drainage has not been accomplished. Lake K'un-yang was originally fed in part by an eastward-flowing P'u-to Ho. This stream was captured by a headward-working tributary of the Yangtze Kiang, reversing the direction of flow and providing an outlet for the lake (fig. 1). Other examples of stream capture are indicated by the barbed appearance of tributary streams in the basin vicinity.

Rock Outcrops

Rocks ranging in age from Cambrian through Quaternary outcrop in the Kunming Area (Brown, 1914). Of these only



Late Paleozoic and Quaternary strata are sufficiently widespread to be of topographic importance. Exposures of Cambrian sandstones and shales, for example, occur only where faulting activity has brought them within the scope of vertical dissection.

Late Paleozoic (Middle Carboniferous) sandstones and limestones form low ridges above the lacustrine plain south of

Lake K'un-yang near Chin-ning and Kun-yang and between Chin-ning and Cheng-kung southeast of the lake (fig. 1). The P'u-to Ho outlet north of Kun-yang is floored with these rocks. Other exposures occur in the basal portions of escarpments north of Yunnan-Fu and west of Lake Yang-tsung.

Most of the country west of the basin is underlain by limestones (Upper Carboniferous), strata also largely responsible for the near-karst topography north of Yunnan-Fu. Exposures of these rocks occur in the base of the Sin Chang Cliffs west of Lake K'un-yang, the upper portion being composed of similar but younger limestones (Permo-Carboniferous) (plate 2, fig. 1). Much of the highland area north, northeast, and east of the lake basin is underlain by the latter limestones with local outcrops of lava, shale, and sandstone.

The basin floor is underlain by Quaternary lacustrine deposits consisting of interfingering layers and lenses of unconsolidated clay, silt, sand, and gravel. Lignitic concentrations occur throughout. Local accumulations of gravel and cobbles indicate deposition by torrential streams. Alluvial fans are present at points of debouchment of stream channels along the basin sides. Finer clastic materials are found in the deltaic projections of the lake shore, as at Yunnan-Fu, Cheng-kung, Chin-ning, and Kun-yang (fig. 1).

Quaternary terraces along the eastern side of the basin are lithologically similar to the more recent deposits of the basin floor. These are dissected remnants of old fluvio-lacustrine plains, each representing an interval of alluvial fan and deltaic construction during a temporary halt in lake-level subsidence. Detailed examination was not possible at the time of collection of data for this paper. However, the undulatory appearance of the terrace surfaces and the character of the deposits lends this thesis greater strength than mere assumption. Additional study may show a relationship between the lake terraces and fluvial terraces further downstream in the Yangtze drainage system.

Observations made in the lower hills along the eastern side of the basin, at somewhat greater elevation than the highest terraces, revealed the presence of disoriented, tilted blocks of thinly bedded, silty clays, sandstones, and lignitic layers of semi-consolidated nature (plate 1, fig. 1). These strata occur at lower elevations than the Paleozoic limestones which con-

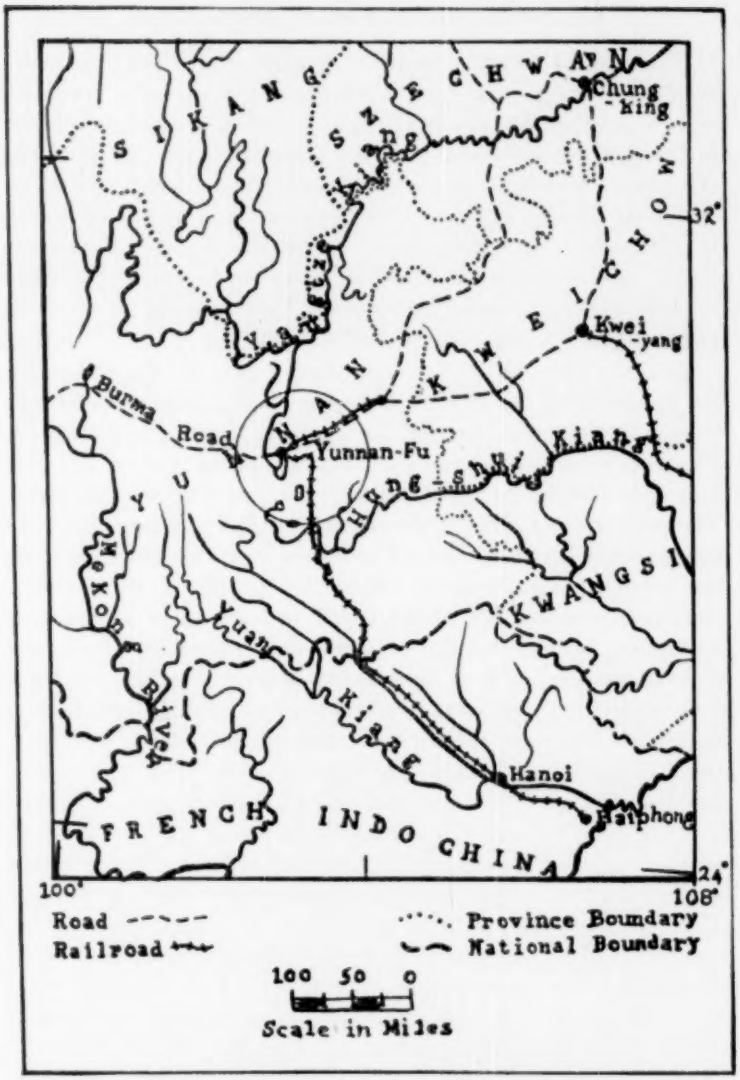


Fig. 2. General map of southwestern China showing major drainage lines and existing communications.

stitute the higher ridges. The beds contain unidentified vertebrate remains and, according to local scientific opinion, are upper Pliocene. The jumbled attitude is the result of faulting.

SUGGESTED PHYSIOGRAPHIC DEVELOPMENT

The rugged, deeply dissected terrain, with steep, relatively fresh-appearing escarpments, favors belief that the Kunming Area is tectonically active at present. Further evidence is found in the modern earthquake record (Cressey, 1934, p. 36). The structural trends of the region, according to Lee (1939, p. 309), are approximately north-northeast and south-southwest, this also being the alignment of the lake basins. The south China region is believed by Lee to have been folded and elevated in late Mesozoic time, the modern basins being of tectonic origin aligned along the axes of folding.

Brown (1914, p. 115) postulated a late Tertiary age for the inception of the modern topographic development, the lake basins having been formed by faulting toward the close of Pliocene. Perhaps old zones of weakness produced by the late Mesozoic folding provided a locale for late Pliocene tectonics. The present bold relief is the result of uplift and faulting, with accompanying stimulation of erosional agencies down through the present. Deprat, as quoted by Lee (1939, p. 206), claims abundant evidence for recent uplift in Yunnan of as much as 6500 feet, though this figure would seem excessive. There can be little doubt, however, that uplift is occurring. The narrow, deep valleys, a dominant topographic element in the region, indicate a continuous stimulus to stream erosion. Furthermore, the lake basins are being tapped and gradually drained as the deepening valleys encroach into these formerly enclosed areas. The steep, 2000-foot Sin Chang Cliffs, in the present writer's opinion, represents only slight modification of a fault scarp along which faulting may still be potential (plate 2, fig. 2). The tilted blocks of Tertiary sediment (Pliocene ?) along the eastern side of the basin show that faulting occurred subsequent to deposition of these strata.

Brown (1914, pp. 118-119) recognized evidence for several stages in the tectonic and erosional history of the region. He cited an accordance of summits east of Lake K'un-yang as representative of a late Pliocene erosion surface, the Tanghien erosional stage of Willis (1907, p. 99). A rather noticeable widening in the upper portion of the P'u-to Ho valley walls is also pointed to as a relic of this stage. This interval was presumably one of broad valley development which, accord-

PLATE 1

Fig. 1. Panorama of the Kunming basin from the east. The high rimming hills are visible in the background. Late Tertiary sediments (Pliocene ?) occupy the immediate foreground.

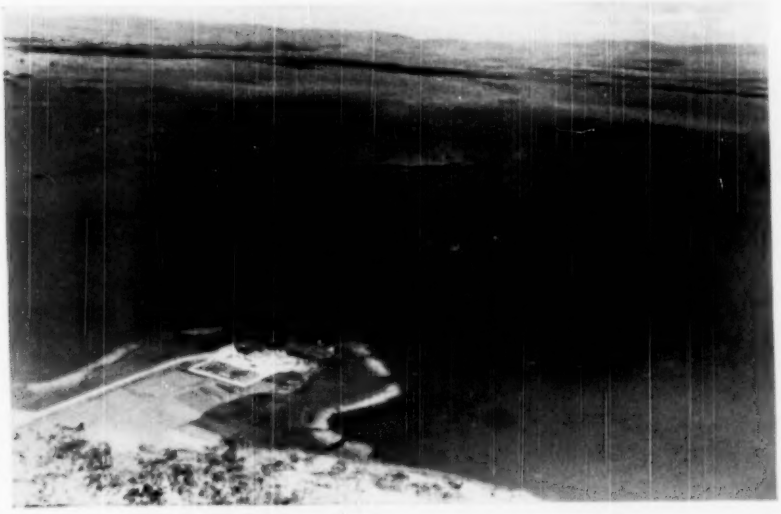


Fig. 2. View eastward from the Sin Chang Cliffs across Lake K'un-yang. The flat lacustrine plain with terrace remnants standing slightly higher is visible in the background.

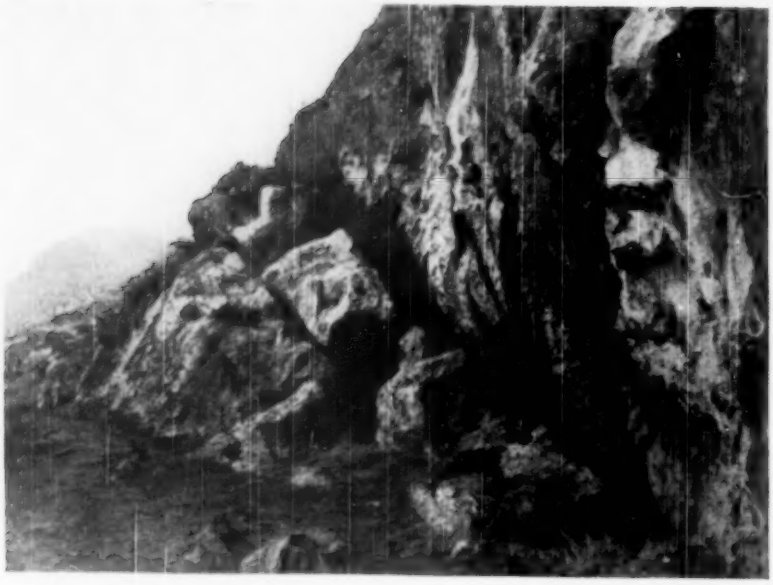


Fig. 1. Steeply westward-dipping Permo-Carboniferous limestones in the upper portion of the Sin Chang Cliffs west of Lake K'un-yang.

Fig. 2. View south along the Sin Chang Cliffs which rim the western edge of Lake K'un-yang. This escarpment is a fault scarp only slightly modified by erosion. The outcropping strata, Permo-Carboniferous limestones, dip westward into the face of the cliff.

ing to Brown, was terminated by faulting and basin development. In early Pleistocene these basins accumulated lacustrine and fluvial deposits, this being the Hinchou aggradational stage of Willis. This phase is reputed to be in progress at present in the Yunnan region.

The present uplift and drainage adjustment, placed by Brown in the Fon Ho stage (Willis, 1907), may have had its origin in late Pliocene or early Pleistocene. The establishment of drainage systems, deepening of valleys with uplift, and the tapping of the lake basins are the results of this activity. The diversion of Lake K'un-yang into the Yangtze Kiang system, as well as capture of the Yang-tsung, Fuhsien, and Chilu lake drainages, are thought to have been part of this process.

Deprat (Brown, 1914, p. 122) contended that in eastern Yunnan the interval from late Pliocene to the present is divisible into five erosional episodes, separated by periods of relative stability. The present writer does not have sufficiently detailed evidence to refute or support this contention. Critical examination of the Yunnan lake terraces should divulge important facts. A thorough study of the hydrographic development of late Tertiary and Quaternary time is needed.

A relationship suggested is the correlation of lake terrace development with regional climatic fluctuations. Harland (1943), working in western Szechwan north of Yunnan Province, found evidence favoring climatic change during the Pleistocene. Lee (1939, pp. 367-399) also favored this view. Cotton (1944, pp. 272-274), in review of a paper by Richardson (1943) concerned with terraces in western Szechwan, suggested that the terrace gravels along the river valleys may have been deposited during the moist intervals when the supply of debris to the drainage was at a maximum. As precipitation decreased in a subsequent drier interval vertical incision of these deposits occurred. The increased erosive power of the runoff, despite a decrease in rainfall, is attributed to the lessening in quantity of debris supplied by weathering. Repetition of such alternating conditions, along with continuous uplift, resulted in terracing of the valley bottom deposits.

The present writer is in sharp disagreement with this suggested sequence of events. Field data gathered in somewhat similar climatic regions in North America fosters a different view (Tator, 1949). In a region of continuous uplift moist

intervals are times of increased drainage incision, the runoff being less hampered by excess of clastic load. Interstream slopes are temporarily stabilized by the increase in vegetative cover. Chemically controlled weathering processes predominate, the result being that the products are of finer nature. Runoff, fed by the more uniform precipitation, is constant. Drainage lines, unhindered by the clogging effect of coarse debris, are able to maintain permanent channels. On the other hand, minimum downcutting prevails under arid conditions. Decrease in precipitation reduces the vegetative cover thereby decreasing the stability of slopes. Physically controlled weathering produces coarse detrital fragments. Rainfall is less uniform, in fact, is usually torrential and of spasmodic occurrence. Runoff is intermittent and the drainage lines become choked with debris. The streams experience difficulty in maintaining a single line of flow, the latter being a requirement for deep valley incision.

Such could have been the history of the development of the Kunming basin terraces. Intervals of greater moisture caused drainage incision and lowered the lake level. Greater aridity, however, temporarily stabilized the lake level as the outlet became clogged with debris, causing accumulations of fluviolacustrine material on the floor of the basin. A succeeding, more humid interval then led to clearing of the outlet and lowering of the lake level. Repetition of this process may have yielded the terrace sequence. The vertical spacing between successive terraces would be controlled by the rate of uplift and the duration of the moist episode whereas the thickness of the individual terrace deposits would indicate the length of the drier climatic phases.

It is believed that the pre-Pleistocene climate in this part of Asia was arid to semi-arid. The incidence of glaciation was brought about by increased precipitation on the higher mountians of western China. It is not illogical to expect that peripheral areas to the south and east of the centers of ice accumulation must also have been affected. Thus, while the glacial stages were perhaps times of increased precipitation, the interglacial stages may have been times of climatic shift toward normal, or aridity.

SUMMARY

The Kunming basin includes a broad lacustrine plain fringed by lake terraces and enclosed by rugged, mountainous terrain. The surrounding highlands are underlain for the most part by late Paleozoic limestones, dissection of which has produced a near-karst topography. This region has been orogenically active since late Pliocene and uplift is still in progress. The basin formed in late Pliocene or early Pleistocene along structural trends established during the late Mesozoic. Capture of the drainage of the basin was accomplished by a tributary of the Yangtze Kiang system in early Pleistocene. Under the influence of continuous uplift and moist climatic intervals, perhaps during the glacial stages, the level of Lake K'un-yang has been progressively lowered. Each lake terrace represents an interval of temporary stabilization of lake level due to alluvial damming of the outlet under a more arid climatic regime. It is felt that the more arid episodes may correlate with interglacial stages. If this sequence of events should prove adequate to account for the Kunming basin terraces it should also be applicable to the other basins of southwestern China.

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DISCUSSION

A paper entitled "Processes of Erosion on Steep Slopes of Oahu, Hawaii"; by Sidney E. White, was published in the March, 1949, issue of this Journal, pp. 168-186. This paper is a condensation of a thesis which briefly describes Oahu, its Koolau Range, and in particular gives a discussion of the factors thought responsible for the steep-walled, theater-like valleys on its leeward side. Manoa Valley is selected as typical and discussed in detail. Much of the article consists of quotations or rephrased statements drawn from Davis, Cotton, and Hinds on geography, Stearns, Vaksvik, and Wentworth on geology, Carson, Jones, and MacCaughey on meteorology, and MacCaughey on ecology. Nowhere in the paper is any statement as to how many trips were made by White or how much time over what period was spent in his study of Manoa Valley. The impression in Honolulu is that the period White spent in these field studies, while in war service, was brief.

An account of the vegetation of Oahu is given, by abstracting to two paragraphs, material from MacCaughey's report on Manoa (1917). White continues (p. 173), "Other leeward valleys may be divided into similar zones." Some may and some may not, due to the strikingly different microclimatic and corresponding ecologic zones on Oahu. It would have been better to refer to actual studies of such valleys, as that by Hosaka on Kipapa Gulch (1937), and that by Egler on arid southeastern Oahu (1947), instead of assuming that all leeward valleys of the Koolau Range had a similar ecologic zonation. His inference that they are all alike is far from the fact.

White's account of the general geology, and description, mapping, and figuring of the geography is largely drawn from dependable sources, and I will not challenge it. On the other hand, after twenty-one years of residence in Manoa Valley and much field work, research, and teaching of botany and ecology as evidenced in the Hawaiian Islands, I feel impelled to deny White's statements of ecological facts and to differ from his conclusions. His main thesis is that on steep slopes in the mountains in the high rainfall belt, the typical succession is (p. 182) as follows: "(1) fresh bedrock exposed; (2) the establishment and succession of mosses, plants, ferns, and trees to the culmination of maximum plant relationships possible, with accompanying soil development to great depths; (3) long and continued use of all available soluble minerals and organic matter; (4) final exhaustion of the soil mantle with deterioration of the plant societies, and alteration to a degenerate growth of grasses; (5) desiccation and hardening of the mass of soil, decaying litter, and rotting humus; (6) instability of the mass of debris produced during prolonged rainfall; and (7) catastrophic avalanching exposing fresh bedrock slopes again."

White's inspiration seems to have come from Freise, a geographer,

who announced in 1938 observing a succession from granite, to forest, to a decadent forest on exhausted soil, to grass,—then avalanching to bedrock. Not having visited the particular granite mountain in Brazil, I cannot express an opinion on its vegetational succession. However, in my own travels and explorations, and I have studied many granite mountains, I know of no place on granite or any other rock where an undisturbed natural forest exhausts its own soil and starves itself out, and is then replaced by grasses. Furthermore, it is not clear to a plant ecologist just what White has in mind when he refers to the grass stage as "a degenerate growth of grasses." A recent scholarly taxonomist, Hutchinson (1934, p. 7), places them at the apex of an upper branch of the family tree of the Monocotyledones. In growth and production, instead of degeneracy, they show great self-sufficiency and adequacy to perpetuate themselves, to nourish themselves, and largely to feed the human race and most grazing animals.

White does not state his reason for reporting in detail only on Manoa Valley. Other more remote valleys would have been more primitive. Of course, Manoa Valley is easy of access, with paved roads almost to the talus slopes, two bus lines for transportation, etc., but as it is near the center of the city of Honolulu, it has, in the last 150 years, suffered from the depredations of man and his domestic animals. The forests have been much reduced in area, depleted, invaded by weeds and exotics, heavily grazed by horses, cattle, and goats, and in areas deforested by the abundant feral pigs. Deforested areas, even on the high, rainy slopes, are often densely vegetated by grass and herbaceous weeds or ferns, but these do not play the important part in initiating landslides (soil avalanches) that White asserts.

White says (pp. 180-181) of the valley head, "Some parts of the slopes are mantled with a thick soil and well-developed plant society, other parts with thick soil and stunted, scrubby grass growth. Certain other sections maintain no soil at all, but instead are sheathed with yellow-brown mud so thin that layered volcanic cinders can be seen beneath. The soil and vegetation on the slopes are in various stages of development from youthful thin soil to maturely developed thick soil, and old thick soil. No ecologic zoning can be distinguished; distribution of variegated patches of vegetation has no obvious relation to topography or climate." White seems fond of an ecological approach, but seems to have little familiarity with its details or meaning. He certainly seems to dislike grasses, but it should be pointed out that a grassy growth can be a well-developed plant society. He does not explain his view that mud is not soil, nor how thin, transparent mud remains on top of bedded volcanic cinders. In reference to his concluding sentence of the paragraph quoted above, as to there being no zoning

and no relation between the vegetation and topography and climate, well—the only comment I can make is that it is not so.

Landslides on the steep forested slopes do occur and the figures quoted by White are striking and significant. They were published by Wentworth following eight years of intensive field work. Certainly landslides play a part in soil movement from steep upper slopes to the gentle valley floor below. The slides are seen in many places, mostly on steep slopes of 40° or more, but they often occur starting in and cutting a strip right out of a healthy, vigorous, virgin, climax forest. After the slide, the invading vegetation of the secondary succession is often rich in grasses, as *Paspalum conjugatum*, etc., but often of other weeds, as *Erechtites hieracifolia*, and *Cuphea carthagenensis*, or of indigenous vines, shrubs, or trees, as *Phyllostegia grandiflora, Perrottetia sandwicensis, Pipturus albidus, Dicranopteris linearis, Lycopodium cernuum, Scaevola mollis, Metrosideros collina,* etc., depending on the habitat, the surrounding vegetation, and source of seeds.

The conditions that cause landslides (soil avalanches),—probably a rainy period that has saturated the soil, followed by torrential rains (such as 5 inches per hour) and high winds, cause landslides on the very steep valley walls, whatever the vegetation, whether thin soil with little vegetation, grasslands, open forest invaded by weeds, or dense virgin forests which show no sign of self-starvation.

My final comment on White's paper is that it contains little original material other than his hypothesis on plant succession as the cause of avalanching on steep basaltic head walls of Manoa Valley. He gives no verifiable data of his own on plant succession or indication that he could recognize one plant from another of the list that he apparently compiled from MacCaughey, or that he has any competence to judge and interpret the stages of a plant succession in Hawaiian vegetation. His hypothesis that avalanching is the result of soil exhaustion by the rain forest which suffers self-destruction and is then succeeded by a "degenerate growth of grasses" which permits soil avalanching is, in my opinion, unproven and is contrary to all that is known of plant succession in Manoa Valley and the Hawaiian Islands.

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REPLY

Response to the paper by S. E. White on the processes of erosion on the steep slopes of Oahu, Hawaii (1949), on the whole, has been favorable. The objections offered by Harold St. John in the preceding discussion present an appropriate opportunity to discuss further the problems of slope erosion in tropical and semitropical regions.

As stated in the introduction to White's paper (p. 170), a brief discussion of the climate, vegetation, and soil of Oahu was reviewed for possible comparison with other tropical and semitropical regions by readers not familiar with the Hawaiian Islands. Under no circumstances was this review of the literature intended to convey originality. It was carefully and completely documented, as St. John's discussion testifies.

The interrupted nature of the field work in the region was a consequence of wartime conditions. Time was not available to organize extended trips, to visit the other Hawaiian Islands, or to descend the cliffs at the heads of all the theaterlike valleys, inasmuch as White lived in Manoa Valley a total of seven months compared to St. John's twenty-one years.

The problems raised by Stearns and Vaksvik (1935), Stearns and Macdonald (1947), Wentworth (1928), Wentworth and Winchell (1947), and White concerning slope erosion in the Hawaiian Islands have not yet been discussed or answered. Some of these problems are here rephrased and summarized.

1. "The talus veneered bedrock slopes in the leeward valleys may be increasing in width at the expense of the cliffs. If this is true, the erosional processes which produced the steep cliffs are no longer as operative as in the past." (White, 1949, p. 174). Are the talus veneered bedrock slopes gaining in area and importance to the disadvantage of the steep cliffs?

2. ". . . the presence of hydrophytic mosses growing on the face of the cliffs along the course of the falls in the leeward valleys studied suggests the inability of the falls to incise on the face of these cliffs today." (p. 176) Are the high waterfalls no longer actively incising canyons in the bedrock today? If this is true, what changes in stream regimen are responsible for the reduced effectiveness of such erosion?

3. "Cliffs rim the heads of the valleys, a few being 200 to 300 feet high with 70 to 80 degree slopes. Above these cliffs, hanging valleys open upwards and extend back to the main summit ridges of the Range. The sides of these hanging valleys often have slopes of 45 to 65 degrees." (pp. 174-175) Do the hanging valleys above the steeps cliffs indicate an older period of greater erosion by the main streams?

4. "A considerable amount of talus veneers the bedrock slopes at

the foot of the cliffs and occupies the floors of the upper valleys. This suggests that erosion is no longer as active as it was in the past, and that changes have occurred which prevent streams from keeping the upper valley floors clear." (pp. 176-177) Does the present condition of the upper valley floors indicate climatic change, general reduction of mountain heights by erosion, or reflect the effect of recent island submergence? What combination of these or other factors has produced this result, and who will advance the statistical information for proof?

5. Wentworth in 1928 (p. 395) summarized the reasons for the great amount of chemical weathering that occurs. "The very great porosity of the Hawaiian rocks, the high average rainfall, the relative ease of decomposition of the minerals composing the basalts, and the high mean annual temperature combine to produce very rapid chemical weathering in the islands, a condition shared, of course, with many other tropical regions." To what extent is the incision of valleys on Oahu and elsewhere dependent upon these factors? Does the more active chemical weathering near the water table level control the configuration of the theaterlike valleys or barrancas?

6. The release of confined water in the dike complex in the Koolau dome (or in any volcanic dome), tapped by both tributary and master streams, as mentioned by Stearns, (1935, p. 25), adds to the perennial water supply and accelerates stream capture. How much does this additional water supply affect headward erosion? Will it account for the incision of certain valleys and not for others?

7. "Captured tributaries entering a master stream form a rim of coalescing plunge pools about the amphitheater wall at the break in the stream gradient. The narrow ridges between the plunge pools are undercut and fall by their own weight . . ." How effective is plunge pool action in the development of a theaterlike valley or barranca where captured tributaries are not involved?

9. Macdonald (1947, pp. 77-78), in discussing the amount of Na, SO_4, Mg, and Ca in the ground water of a drilled well from the island of Molokai, states that these radicles "cannot be solely the result of mixing of pure fresh water with sea water. In part, they have probably been derived by solution from the enclosing rocks. The high temperature of the water in that well . . . suggests, however, heating of the ground water by rising volcanic volatiles, and some of the dissolved material has probably been brought upward with the volatiles." Here is an attempt to identify the sources of solids in the ground water in which some are derived by solution from the volcanic rocks. Yet how important is solution in the removal of decayed material, and in land reduction?

9. "If sufficient soil, muddy particles, and decomposed rock

debris are carried out from beneath large enough areas of thick matted masses of plants, the forest is thereby lowered onto less decomposed bedrock. Further chemical decomposition will occur, and the surface of solid bedrock beneath the talus thus becomes weathered down to a lower level." (White, 1949, p. 179) Mud flows in the coastal mountains of Brazil break out through the forest floor and thus lower the vegetation onto relatively fresh bedrock beneath. To what extent is this process present in the Hawaiian Islands? What statistical evidence can be advanced to substantiate the effectiveness of this method of erosion under semi-tropical conditions?

10. Movement of small particles of weathered volcanic rocks across steep slopes is important in the reduction of mountain areas. What is the relative significance of water transport, soil flow and soil creep on the slopes of various degrees both in the Hawaiian Islands and elsewhere?

11. Wentworth and Winchell (1947, p. 63) stated that soils may develop a pelletlike structure which renders them resistant to erosion. This resistance, in addition to a heavy forest cover, helps to maintain a thick soil even on very steep slopes. "Locally the deeper weathered material becomes rammed into a compact mass which can stand in steep slopes." What effect does sublaterite development have on the maintenance of steep slopes? The sublaterite soil develops on lower slopes where oxidation and accumulation of iron occur. With the lower temperature and greater rainfall, reducing conditions and the loss of iron are possible on upper slopes. Is soil flow and soil creep hindered on lower slopes by tight sublateritic soil and relatively favored on upper slopes? What are the limits for slopes produced by avalanching and mass movements below which such processes of erosion do not ocur?

12. The soil and vegetation on the steep cliffs is in various stages of development. Depth of soil varies from thick soil with a well-developed plant society to a thin "soil" so thin that the texture of layered volcanics can be seen through the weathered cover. It is assumed that the differences in soil thickness result from differential soil removal, partly by avalanching. What specific influences have plants in generating or delaying mass movements of the soil?

13. " . . . maintenance of the slopes has depended upon avalanching as a method of erosion in the past, and . . . avalanching and mass movement of particles of weathered rock debris control the recession of the steep slopes today." (White, 1949, p. 181). Avalanching is significant in slope reduction in the Hawaiian Islands, but whether less or more today than in the past is still to be determined. White properly stated, "Any further argumentation would be

pure speculation at this writing; proof of such erosion for the past will be revealed only by further field work." (p. 182).

To repeat again, there is a great need for additional, accurate, discriminating and reported investigation of the processes of slope erosion in all climatic regions. Constructive response from all sciences is essential for the solution of the many problems suggested herein for consideration. White's paper is but a small contribution, his start in the direction toward a study of erosion in semitropical regions. If it has attracted attention to the lack of data regarding the mechanics of slope erosion, even among a small group, its publication will have been justified.

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REVIEWS

Mechanics, Statistics and Dynamics; by MERIT SCOTT. New York, 1949 (McGraw-Hill Book Co., Inc., $4.50).—If the present trend in teaching physical dynamics can be characterized in a single phrase it might be "back to fundamentals," and several excellent texts epitomizing this trend have appeared in the last few years. The reasons for this reaction are many: the enormous increase in material to be taught and the correspondingly diminished time devoted to dynamics, the necessity of putting dynamics into its more general forms for the purposes of quantum theory, the discrediting of mechanism and the loss of fascination for dynamics per se, and others. It is with some surprise, then, that one scans the present text, for by the author's admission it is modeled upon the authors of another era. Here we find the detailed treatments of the many and complicated problems so dear to the Victorians, whereas general principles and methods fill subsidiary roles. While I cannot condemn the book in the field in which the author chooses to operate, I find it out of tune with the times, excellent as a reference text, but not fitted to the needs of the present student of physics who must master the principles of dynamics in its general form.

ROBERT BERINGER

Principles of a New Energy Mechanics; by JAKOB MANDELKER. Pp. viii, 73. New York, 1949 (Philosophical Library, $3.75).—The present thin volume adds itself to the list of critiques of relativity theory which were so numerous two decades ago. As is usual the author twists one of the relativity postulates in a slightly different way and unleashes a new set of dynamical formulae. The reviewer does not hold with the deductions obtained thereby.

ROBERT BERINGER

Basic Theories of Physics: Mechanics and Electrodynamics; by PETER G. BERGMANN. Pp. viii, 280. New York, 1949 (Prentice-Hall, Inc., $3.75).—The revolution in physics which dates from the successes of relativity theory and quantum mechanics is only now recasting the basic instruction of graduate students, and the full integration of these changes into elementary teaching is hardly begun. True, various specialty courses are offered in the new theories together with phenomonological reviews of their experimental bases, but the student is likely to find that his training in classical physics has been directed toward nineteenth century objectives, and he undergoes an abrupt transition to the philosophy and analytic methods of the newer disciplines. The present book is apparently designed to soften this transition and to prepare the student more fully for the modern theories. Mechanics is developed from New-

ton's laws, and is carried through analytic dynamics, the mechanics of deformable bodies, and hydrodynamics. Tensor notation is introduced at an early stage and mathematical sections are interspersed throughout. The notation alone is quite unique in books at this level. In the second part electrodynamics is developed through the Maxwell equations and the theory of special relativity. Here the approach is fairly standard but the critical appraisal of the equations and the emphasis on those features most basic to later study are carefully conceived and should be most rewarding. Chapters on wave propagation and the electrodynamical aspects of optics conclude the text. The clarity of exposition and selection of topics is uniformly good, and the interpretative sidelights are excellent. Of these latter, the discussion of the incompatibility of mechanical and field theories impresses me most. My only criticism on a first reading is in the matter of proofs which are sometimes a trifle too elegant or foreshortened. ROBERT BERINGER

The Crystalline State. Vol. I, A General Survey; by W. L. Bragg. Pp. 352; 187 figs. Third printing, London, 1949 (G. Bell & Sons, $8.50).—In 1933 appeared the first volume of an ambitious trilogy, *The Crystalline State*. This volume, entitled *A General Survey*, by W. L. Bragg, was to serve as a general introduction to two more highly specialized volumes prepared by other experts. For various reasons, only Vol. I appeared in print. Recently, however, this almost forgotten project received a new lease on life when an author was found for Vol. II, on X-ray optics. Vol. III still seems to be in the embryo stage. Advantage has been taken of the appearance of the second volume to reprint the first.

It is unfortunate that the opportunity to bring the old volume up to date was not taken at the same time. No references later than 1932 appear, except in the two-page bibliography; prospective purchasers, who might be under the impression that they can buy a revised edition, should look again. Moreover, the price seems unduly high, and the cost is not reflected in a first-rate publishing job. For example, Fig. 75 in the review copy, showing radii of atoms in metals, is almost illegible; there seems to have been an ink shortage during the printing of Fig. 77 and 78 (AX and AX_2 Structures).

When all is said and done, however, the book remains perhaps the best elementary introduction to X-rays and crystal structure. Most of it could be readily understood by a bright undergraduate. Indeed, the undergraduate might also make the surprising discovery that profound scholarship in science is not, of itself, a bar to brilliant writing. VICTOR GILPIN

Surface Active Agents, Their Chemistry and Technology; by A. M. SCHWARTZ and J. A. PERRY. Pp. xi, 579; 51 figs. New York, 1949 (Interscience Publishers, Inc., $10.00).—This book concerns those solutes which greatly lower the surface energy of their solvents; the commonest examples of these solutes are, of course, detergents and wetting agents. Here is an exhaustive survey of all the applicable theories and a description of all the practical aspects, including a useful and original classification of surface active agents, methods for measurement and evaluation of their properties, preparative methods and uses.

The authors have aimed at universal appeal by devoting a section to nearly every field connected with surface activity. They apparently hope thereby to interest everybody, all the way from the academic physical chemist to the "Dreft" salesman. There is, therefore, the possibility that each potential and specialized reader might seek his desired information from more specialized sources, but no doubt there is a large middle group of workers who will find here a wonderful time-saver, a bibliography-with-interpretations, covering the length and breadth of a highly fertile field (albeit a somewhat less than fascinating field when regarded in such complete and magnified detail).

The section on "the physical chemistry of surface active agents in theory and practice" should be strongly recommended to any interested person who is not thoroughly familiar with this branch of physical chemistry. In this section are to be found some original thoughts which should be of permanent value in the field and in which may reside the most lasting value of this effort.

Far from leading one through scientific adventure, this practical book is nevertheless extremely useful. It is an exhaustive exposition —exhaustive to a very reasonable degree—of all possible considerations of theory and practice in the fields of wetting agents, detergents and emulsifiers, and it will probably become a standard reference and bibliography text.

ELLIOT S. PIERCE

Diamond Tools; by PAUL GRODZINSKI. Pp. xvi, v-viii, 392; 222 figs., 61 tables. London and New York, 1944 (20/s, N. A. G. Press; $4.50, Anton Smit and Company).—This volume packs many data into a small space. It includes descriptive chapters with bibliographies on the following subjects: diamond production and trade; diamond as a technical material; diamond and other jewel bearings; hardness testers; grinding-wheel dressers; tools for machining metal; machining of glass; machining of building stone; rock drilling; engraving; wire dies; abrasive powders. Many industrial uses (and

limitations) of diamond are described with great detail for the finest points of technique.

Mr. Grodzinski has written much on various aspects of the subject; this book adds to, and thoroughly summarizes, his previous writings. HORACE WINCHELL

The Boylston Street Fishweir II; by ELSO S. BARGHOORN, PAUL S. CONGER, SHELDON JUDSON, FRED B. PHLEGER, and L. R. WILSON; edited by FREDERICK JOHNSON. (Papers of the Robert S. Peabody Foundation for Archaeology, Vol. 4, No. 1.) Pp. 133; 14 plates, 15 figs., and 17 tables. Andover, Mass., 1949 ($2.00).—Discovery in 1946 of part of an Indian fishweir in excavations for the John Hancock Life Insurance Company building on Stuart Street, Boston, has made possible a continuation of the studies of the same or a similar weir uncovered in 1939 during construction of the New England Mutual Life Insurance Company building on Boylston Street. The new studies confirm that the fishweir, whose cultural affiliations are not known, was in use about 2,500 years ago, more or less, when the sea was rising relative to the land towards its present level.

The current studies revolve around a core bored to bed rock beneath the fishweir. Primarily through an analysis of the stratigraphy represented in this core, Conger is able in a discussion of the Pleistocene geology of the Boston area to distinguish two local substages of the Wisconsin glaciation and to correlate these with changes in relative sea level. Studies of the paleobotanical material by Barghoorn, of the micro-fossils by Wilson, of the Foraminifera by Phleger, and of the diatoms by Conger provide additional information concerning the environment before, during, and after the succession of sub-stages. Most of these data refer to the time before the fishweir was constructed, but they also indicate, contrary to some previous inferences, that the climate was no warmer when the weir was in use than it is today. IRVING ROUSE

Ancient Man in North America; by H. M. WORMINGTON. (Popular Publications, The Denver Museum of Natural History, No. 4). Pp. 198; 21 figs., 2 tables. Denver, 1949 ($1.50, paper bound; $2.50, cloth bound).—This third edition of the most comprehensive summary of the subject of Early Man in America has been revised from previous editions published in 1939 and 1944. That the number of pages has increased from 89 to 198 is an indication of the amount of research on the subject in the last decade.

The organization of the previous editions is maintained: (1) a description of the major flint and ground stone industries for which

there is geological evidence of antiquity; (2) an areal survey of the sites in which these industries have been found, with the evidence for dating them; (3) a summary of the finds of human skeletal material for which antiquity has been claimed; and (4) a theoretical discussion of the peopling of the New World. While the book is written for the layman and undergraduate student, it is technically accurate and provides an excellent introduction to the subject for any non-specialist.

The author has made a special effort to include the latest, unpublished research and, as a result, the current trends are well presented *e.g.*, the tendency to restrict the use of the terms *Folsom* and *Yuma* to specific types of projectile points and to substitute new terms, such as *Plainview, Sandia*, and *San Jon*, for the variant earlier and later types. A glossary and a detailed bibliography, which includes manuscript reports, are particularly valuable from this standpoint.

In an appendix, Ernst Antevs discusses the geology of the Clovis sites in New Mexico, where classic Folsom, Plainview, and Yuma types have been found. He restates with slight modification his earlier correlation of the Clovis sites with the Estancia Pluvial, a correlation to which some geologists have objected.

IRVING ROUSE

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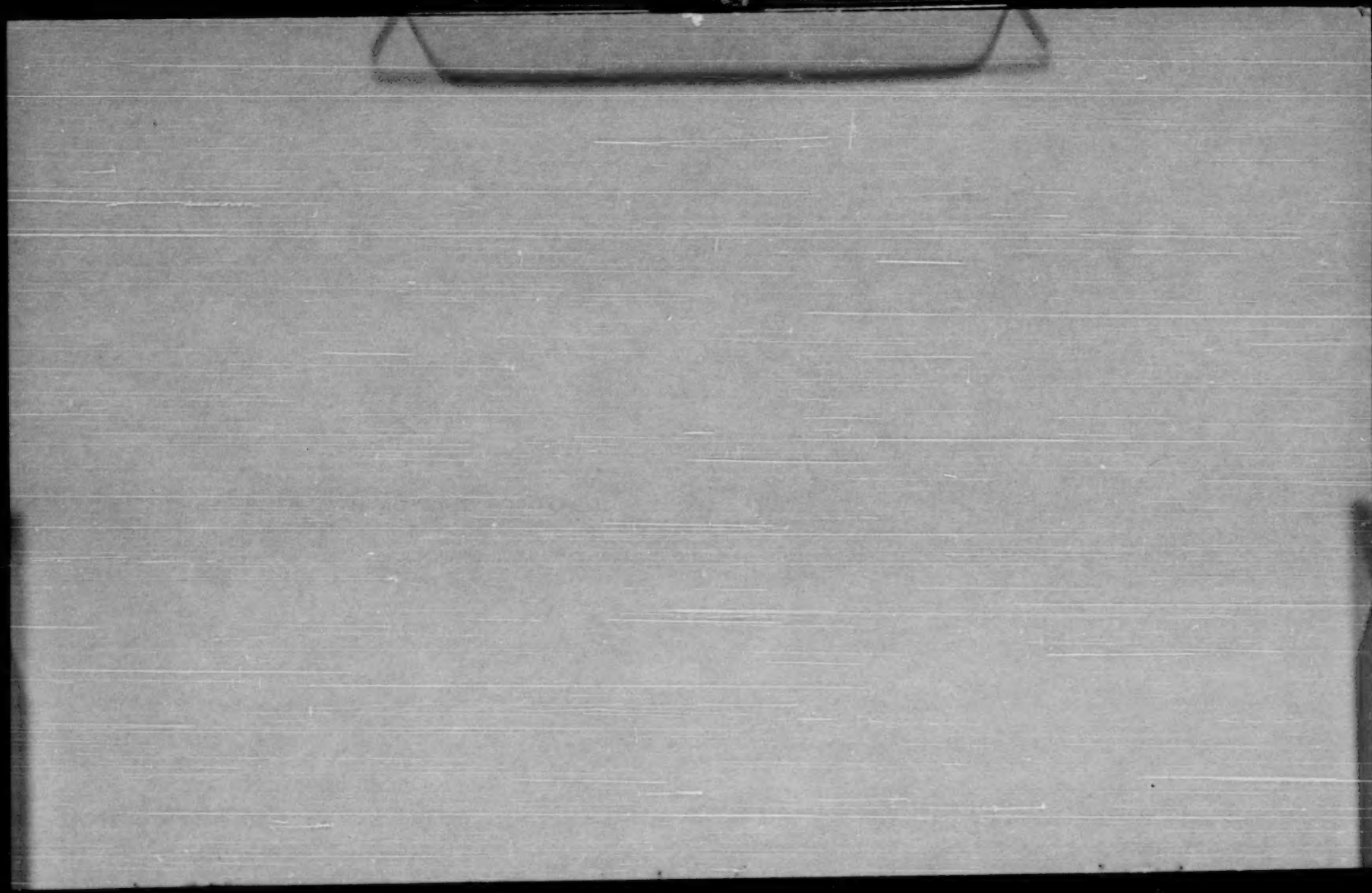

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